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OF THE EARTH

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## ABSTRACT

THE FIRST PART OF THIS REPORT TRACES THE PREGEOLOGIC HISTORY OF THE EARTH ACCORDING TO THE MOST CURRENT ASTROPHYSICAL THEORY OF THE EVOLUTION OF THE SUN AND SOLAR SYSTEM FROM THE PARENT SOLAR NEBULA. IN VIEW OF THE EFFECT ON TERRESTRIAL SURFACE PROCESSES, THE VARIATION OF SOLAR LUMINOSITY WITH TIME IS ALSO CONSIDERED WITH THE SUGGESTION THAT CONCLUSIONS ABOUT THE EARLIEST OCCURRENCE OF RUNNING WATER ON THE EARTH'S SURFACE MAY HELP IN THE CALIBRATION OF THE EVOLUTION OF SOLAR LUMINOSITY. CONCLUSIONS REGARDING THE PREGEOLOGIC ACCUMULATION OF THE EARTH ARE REVIEWED; ACCRETION FROM COLD, SOLID OBJECTS PROBABLY IN THE FORM OF WHISKER-LIKE CRYSTALS IS EMPHASIZED.

THE SECOND PART DESCRIBES DATA AND DIRECT CONCLUSIONS RELATING TO THE OLDEST KNOWN ROCKS WHICH HAVE BEEN FOUND DISTRIBUTED THROUGH A ROUGHLY NORTH-SOUTH BELT IN SOUTHEAST AFRICA, IN THE KOLA PENINSULA OF NORTHWESTERN USSR, IN SOUTH CENTRAL MANITOBA, CANADA AND IN THE NORTHERN ROCKY MOUNTAINS OF THE UNITED STATES. THESE OLDEST ROCKS, WHICH HAVE TERMINAL AGES FROM 3.2 TO 3.6 BILLION YEARS IMPLY EROSIONAL PROCESSES BACK ABOUT 4 BILLION YEARS AGO.

THE LAST PART OF THE REPORT DESCRIBES ASTROPHYSICAL AND GEOLOGICAL CONCLUSIONS DERIVED FROM A CONSIDERATION OF THE OLDEST ROCKS AND MODERN CONCEPTS OF THE ORIGIN AND ACCUMULATION OF THE EARTH.

1. FROM THE INFERENCE THAT RUNNING WATER EXISTED AT LEAST 4 BILLION YEARS AGO, IT SEEMS THAT TEMPERATURES WERE MOSTLY ABOVE-FREEZING AT THIS TIME. SINCE THE PRIMITIVE ATMOSPHERE IS SHOWN TO HAVE HAD A LOWER GREENHOUSE EFFECT THAN AT PRESENT, SURFACE TEMPERATURES MUST HAVE BEEN CONTROLLED BY SOLAR LUMINOSITY. ACCORDING TO OUR CALCULATIONS OF TERRESTRIAL TEMPERATURES BASED ON CURRENT SOLAR MODELS, EITHER SOME REVISION OF THESE MODELS IS NECESSARY OR THE AGE OF THE EARTH AND SUN MUST BE GREATER THAN 4.5 AND 5 BILLION YEARS RESPECTIVELY IN ORDER THAT RUNNING WATER EXISTED AT LEAST 4 BILLION YEARS AGO.

2. SINCE RATES OF WEATHERING AND EROSION VARY DIRECTLY WITH TEMPERATURE, ATMOSPHERIC WATER CONTENT AND VEGETATION COVER, ALL OF WHICH INCREASED WITH GEOLOGIC TIME, IT IS SUGGESTED THAT EROSIONAL RATES ALSO INCREASED, AND WERE VERY SLOW INITIALLY. IN TURN, THE PERIOD OF DURATION OF GEOSYNCLINAL CYCLES SHOULD HAVE DECREASED WITH TIME AS EROSION AND RESULTING SEDIMENTATION INCREASED.

3. THEORIES OF THE ORIGIN OF CONTINENTS BY SEGREGATION FROM THE MANTLE CANNOT BE RECONCILED WITH THE TIME SCALE PROVIDED BY CALCULATIONS FROM THE THERMAL HISTORY OF THE EARTH AND THE CURRENTLY ACCEPTED AGE OF 4.5 BILLION YEARS. ARGUMENTS ARE GIVEN IN SUPPORT OF THE HYPOTHESIS THAT THE CONTINENTS ORIGINATED BY IMPACT FROM EXTRA-TERRESTRIAL SOURCES AND WERE MODIFIED BY SUBSEQUENT GEOLOGIC PROCESSES AND MANTLE ADMIXTURE.

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## INTRODUCTION

AS THE DATING OF THE OLDEST ROCKS IN THE EARTH'S CRUST IS PUSHED FURTHER BACK IN TIME, THE INTERPRETATION OF EARLY GEOLOGIC PROCESSES BEGINS TO MERGE WITH THE REALM OF ASTROPHYSICAL THOUGHT RELATING TO THE ORIGIN OF THE SUN AND EARTH AND THE REST OF THE SOLAR SYSTEM. ONE OF THE MOST SIGNIFICANT DEVELOPMENTS IN ASTROPHYSICS, IN RECENT YEARS HAS BEEN THE CLEAR DEMONSTRATION THAT STARS MUST BE FORMING CONTINUOUSLY. INVOLVED IN THIS SCHEME IS THE MECHANISM OF STAR FORMATION AND EVOLUTION TOGETHER WITH AN ESTIMATE OF STELLAR AGES. IN THE BORDERLAND BETWEEN ASTRONOMY AND GEOLOGY IS THE APPLICATION OF GEOCHEMISTRY, GEOPHYSICS AND ASTROPHYSICS TO DETAILED INVESTIGATIONS OF THE PROBLEM OF THE ORIGIN OF THE EARTH AND SOLAR SYSTEM. AND IN THE REALM OF GEOLOGY, THE DATING OF ROCKS OF GREAT ANTIQUITY PROVIDES THE NECESSARY DATA FOR THE INTERPRETATION OF PROCESSES IN THE PRIMEVAL EARTH. THESE AREAS OF INVESTIGATION MUST ULTIMATELY YIELD A CONSISTENT PATTERN FOR THEY DEAL WITH CONNECTED AND CONTINUOUS STAGES IN THE DEVELOPMENT OF THE SUN AND EARTH.

ALTHOUGH ANY CURRENT ATTEMPT AT A SYNTHESIS MUST BE A HAZARDOUS ONE, WE BELIEVE THE ATTEMPT IS NOW JUSTIFIED IN VIEW OF THE PROGRESS IN THESE RELATED AREAS. AND ALTHOUGH THE ANALYSIS MAY BE ONLY PARTLY SUCCESSFUL, IT MAY NEVERTHELESS INDICATE BOTH CONSISTENCIES AND INCONSISTENCIES IN MODELS

AND THEORIES, AND ALSO SUGGEST WHERE VITAL BOUNDARY CONDITIONS EXIST FOR FITTING THEORY WITH FACT OR OTHER THEORY. FOR EXAMPLE, A SUGGESTION RELATING TO THIS WAS MADE BY SCHWARZCHILD (1958) WHEN HE ASKED WHETHER THE PREDICTED INCREASE IN LUMINOSITY OF THE SUN COULD HAVE HAD OBSERVABLE GEOLOGICAL EFFECTS. AN IMPORTANT, BUT BRIEF EXAMINATION OF THIS POINT WAS MADE BY RINGWOOD (1960).

AS PART OF THIS INVESTIGATION WE PREFER TO REVERSE THE THINKING OF SCHWARZCHILD AND RINGWOOD BY DETERMINING WHAT BEARINGS EARLIEST OBSERVABLE GEOLOGIC PROCESSES HAVE ON THEORETICAL PREDICTION OF INCREASING SOLAR LUMINOSITY. THIS IN TURN HAS FURTHER IMPLICATIONS RELATED TO MANY FACETS OF THE PRIMEVAL EARTH.

THE ANALYSIS IN THIS REPORT IS DIVIDED INTO THREE MAJOR PARTS. IN THE FIRST, A SUMMARY OF THE CURRENT BACKGROUND RELATING TO THE ORIGIN OF THE SUN AND EARTH IS GIVEN IN TERMS OF THE RECENT DATA AND THEORY OF ASTROPHYSICS AND GEOCHEMISTRY. IN THE SECOND PART, A SUMMARY OF THE DATA OF THE OLDEST ROCKS IS REPORTED TOGETHER WITH THE IMMEDIATE CONCLUSIONS RESULTING THEREFROM. THE BROAD ASTRONOMICAL AND GEOLOGICAL CONCLUSIONS DERIVED FROM THE PREVIOUS INFORMATION ARE GIVEN IN THE THIRD AND FINAL PART.

## ACKNOWLEDGMENTS

WE ARE ESPECIALLY GRATEFUL TO PROFESSORS J. L. KULP AND A. POLDEVAART OF COLUMBIA UNIVERSITY FOR MAKING AVAILABLE UNPUBLISHED DATES ON SOME OF THE OLDEST ROCKS FROM EAST AFRICA AND WESTERN UNITED STATES AND FOR THE HELPFUL DISCUSSION THEY PROVIDED. WE ALSO WISH TO THANK SIR HAROLD JEFFREYS AND DR. KURT LOWE FOR THEIR READING OF, AND RELATED COMMENTS ON THE ENTIRE MANUSCRIPT AND DR. WALTER BUCHER FOR HIS HELPFUL DISCUSSION ON CERTAIN OF THE ARGUMENTS. THE RESEARCH AT THE LAMONT GEOLOGICAL OBSERVATORY WAS SUPPORTED BY A RESEARCH GIFT FROM THE U. S. STEEL FOUNDATION.



## ASTRONOMICAL BACKGROUND

### ORIGIN OF SOLAR TYPE STARS

ASTRONOMICAL EVIDENCE INDICATES THAT STARS ARE FORMING CONTINUOUSLY FROM CLOUDS OF DUST AND GAS AS ELABORATED BY BURBIDGE AND BURBIDGE (1958).

UNDER SUITABLE CONDITIONS (HOYLE, 1960; SPITZER, CAMERON, 1962) THESE CLOUDS MAY CONVERT KINETIC ENERGY EITHER TO RADIANT ENERGY WHICH IS LOST TO SPACE, OR TO ENERGY OF MOLECULAR DISSOCIATION AND IONIZATION RESULTING IN CONTRACTION OF THE CLOUD. THESE PROCESSES WOULD LEAD TO INCREASING TEMPERATURE AND DENSITY WITH THE CLOUD BECOMING LUMINOUS AT SOME STAGE. ULTIMATELY, THE CENTRAL TEMPERATURE AND DENSITY WOULD REACH A POINT WHERE NUCLEAR REACTIONS OCCUR RELEASING ENERGY AT A MORE RAPID RATE AND FINALLY CAUSING CONTRACTION TO CEASE. THE INITIAL NUCLEAR ENERGY PHASE IS RELATIVELY LONG IN THE LIFE HISTORY OF A STAR SO THAT MOST STARS HAVE OBSERVABLE FEATURES CHARACTERISTIC OF THIS PHASE. IN THE RUSSELL-HERTZSPRUNG DIAGRAM, WHICH SHOWS STELLAR LUMINOSITIES PLOTTED AGAINST COLOR OR TEMPERATURE, THERE IS A MARKED CONCENTRATION IN A NARROW REGION CALLED "THE MAIN-SEQUENCE" (STRUVE, 1950; ARP, 1958; SCHWARZ<sup>C</sup>CHILD, 1958). STARS IN THIS PHASE OF DEVELOPMENT, SUCH AS THE SUN, ARE THEREFORE REFERRED TO AS "MAIN-SEQUENCE" STARS. DURING THEIR EVOLUTION THEY DEVIATE PROGRESSIVELY AWAY FROM THE MAIN SEQUENCE, BUT THE SUN, WHICH IS AT LEAST 5 BILLION

YEARS OLD STILL LIES WITHIN THIS GROUP INDICATING IT HAS UNDERGONE LITTLE EVOLUTIONARY CHANGE.

IN GENERAL, STARS FORM AS VERY LOCALIZED MULTIPLE SYSTEMS (VAN DE KAMP, 1953) WITH BINARIES PREDOMINATING. ON A LARGER SCALE THEY SEEM TO FORM PRIMARILY IN GROUPS WITH MEMBERS NUMBERING IN THE HUNDREDS. THEORIES OF STAR FORMATION, REVIEWED BY BURBIDGE AND BURBIDGE (1959), ARE NOT DETAILED ENOUGH TO ACCOUNT FOR THESE FEATURES EXCEPT IN A GENERAL WAY. WHATEVER THE PROCESSES OF STAR FORMATION MAY BE, IT IS BELIEVED THAT MAIN-SEQUENCE STARS LIKE THE SUN ARE SURROUNDED INITIALLY BY CLOUDS OF GAS AND DUST. EVIDENCE TO SUPPORT THIS VIEW ARISES FROM THE INTERPRETATION (HERBIG, 1962) OF THE T TAURI CLASS OF VARIABLE STARS AS BEING IN PROCESS OF FORMATION. THESE STARS COVER A RANGE OF SPECTRA WHICH INCLUDES THAT OF THE SUN.

IT IS NOT AN UNREASONABLE HYPOTHESIS THAT UNDER SOME CIRCUMSTANCES, PARTICULARLY FOR SINGLE STARS, A PLANETARY SYSTEM MAY DEVELOP OUT OF THE SURROUNDING NEBULOSITY. THIS IS THE REASONING BEHIND THE CURRENT THEORIES OF THE ORIGIN OF PLANETARY SYSTEMS (HOYLE, 1960; CAMERON, 1962).

IN ORDER TO INTERPRET BOTH CHEMICAL ANALYSES OF METEORITES AND THE EARTH'S CRUST, AND RADIOACTIVE DATING MEASUREMENTS, A KNOWLEDGE OF THE PRIMORDIAL COMPOSITION IS REQUIRED. A THOROUGH DISCUSSION OF ABUNDANCES OF THE ELEMENTS HAS BEEN GIVEN BY SUESS AND UREY (1956). HOWEVER, THEIR DISCUSSION DID NOT TAKE INTO ACCOUNT THE NOW WELL ESTABLISHED

RESULT THAT ELEMENT DISTRIBUTIONS DIFFER AMONG STAR GROUPS IN THE GALAXY (SCHWARZSCHILD, 1958; BURBIDGE AND BURBIDGE, 1958; ALLER, 1958).

THE THEORY OF ELEMENT FORMATION IN STARS STARTS WITH A PURE HYDROGEN GALAXY FROM WHICH THE INDIVIDUAL STARS FORM. NUCLEAR PROCESSES SUPPLY STELLER ENERGY AND IN THE PROCESS CONVERT HYDROGEN TO HEAVIER ELEMENTS. AT A LATE STAGE OF DEVELOPMENT STARS MUST EJECT A CONSIDERABLE FRACTION OF THEIR MASSAS INTO INTERSTELLAR SPACE AS IN THE CASE OF SUPER-NOVAE. THE RESULTING NEBULOSITY LEADS TO A SECOND GENERATION OF STARS ENRICHED IN HEAVIER ELEMENTS. THE SUN APPEARS TO BELONG TO A STILL LATER CYCLE IN WHICH THE CONCENTRATION OF HEAVIER ELEMENTS HAS BEEN INCREASED STILL FURTHER.

#### AGE AND EVOLUTION OF THE SUN

THE AGE OF THE SUN PLACES LIMITS ON THE TIME SCALE FOR FORMATION OF THE EARTH. INITIAL LUMINOSITY AND SUBSEQUENT EVOLUTIONARY CHANGES FOR THE SUN ARE PRIMARY FACTORS DETERMINING THE TEMPERATURE OF THE CLOUD FROM WHICH THE EARTH FORMED AND SUBSEQUENTLY THE EARTH'S SURFACE TEMPERATURE.

THE MAJOR INITIAL EVOLUTIONARY CHANGE IN A STAR IS ITS INCREASING LUMINOSITY. CALCULATIONS FOR THE SUN, FIRST CARRIED OUT BY SCHWARZSCHILD (1958) AND HIS ASSOCIATES SHOWED THAT WITH AN INITIAL COMPOSITION OF 75-80 PERCENT HYDROGEN, AN INCREASE OF ABOUT 40 PERCENT IN LUMINOSITY WOULD HAVE OCCURRED IN ABOUT 5 BILLION YEARS.

IN GENERAL THE AGE OF THE SUN HAS BEEN ASSUMED TO BE ABOUT 5 BILLION YEARS (SCHWARZSCHILD, 1958) ON THE BASIS THAT IT IS NOT MUCH OLDER OR YOUNGER THAN THE EARTH.

HASELGROVE AND HOYLE (1959) HAVE ATTEMPTED TO DEDUCE THE SUN'S AGE FROM THE TIME IT WOULD TAKE A HOMOGENEOUS STAR OF THE SUN'S MASS AND INITIAL COMPOSITION TO EVOLVE TO THE PRESENT SUN. ONCE THE SUN BECAME A MAIN-SEQUENCE STAR THE CONVERSION OF HYDROGEN TO HELIUM IN ITS CENTRAL REGIONS WOULD DESTROY THE HOMOGENEITY BY PRODUCING A GROWING CORE DEPLETED IN HYDROGEN. HOYLE'S CALCULATIONS START WITH AN INITIAL SUN HAVING A HYDROGEN TO HELIUM MASS RATIO OF 3, A VALUE ALSO ADOPTED BY SUESS AND UREY (1956). ALTHOUGH THE RATE OF HELIUM FORMATION IN THE GALAXY IS AN UNCERTAIN QUANTITY, DETERMINATIONS OF THE HYDROGEN TO HELIUM MASS RATIO (ALLER, 1958) FOR LUMINOUS HOT STARS FORMED WITHIN <sup>the past</sup>  $10^8$  YEARS VARY FROM 2 TO 5. BECAUSE THESE STARS ARE MUCH YOUNGER THAN THE SUN, THEY SHOULD CONTAIN RELATIVELY MORE HELIUM.

THE "ZERO-AGE" SUN WOULD HAVE HAD ABOUT 0.7 OF THE PRESENT LUMINOSITY. WITH THE ADOPTED COMPOSITION, 5.4 BILLION YEARS WOULD HAVE BEEN REQUIRED TO ATTAIN THE PRESENT LUMINOSITY. THE RATE OF STELLAR EVOLUTION IS GREATER AT LOWER HYDROGEN CONCENTRATIONS (HOYLE, 1959). FOR TWO STARS HAVING APPROXIMATELY SOLAR LUMINOSITY BUT DEPLETED IN HEAVY ELEMENTS (TYPE II STAR) COMPARED WITH THE SUN, HOYLE FOUND THAT FOR 99 PER CENT HYDROGEN THE TIME SCALE OF

INTENTIONALLY

LEFT

BLANK

CONDITIONS OF ACCUMULATION. - - QUITE CONCLUSIVE EVIDENCE FOR THE FORMATION OF THE EARTH AND METEORITES FROM SOLIDS AT LOW TEMPERATURES HAS BEEN PRESENTED BY BROWN (1952) AND UREY (1957A,B).

BROWN COMPARED RATIOS OF TERRESTRIAL TO COSMIC ABUNDANCES OF THE NOBLE GASES, Ne, Ar, Kr, AND Xe, WITH SIMILAR RATIOS FOR THE MORE REACTIVE GASES,  $H_2O$ ,  $CO_2$ ,  $N_2$  AND  $O_2$ . FOR THE LATTER GROUP THE RATIOS OF TERRESTRIAL TO COSMIC ABUNDANCES ARE MUCH HIGHER THAN FOR THE INERT NOBLE GASES. BECAUSE ALL OF THE ABOVE MOLECULES HAVE COMPARABLE MOLECULAR WEIGHTS, GAS PHASE FRACTIONATION IN A GRAVITATIONAL FIELD COULD NOT HAVE PLAYED AN IMPORTANT PART IN THEIR ACCUMULATION. THE REACTIVE GASES MUST THEREFORE HAVE BEEN RETAINED CHEMICALLY IN SOLIDS UNTIL THE EARTH WAS LARGE ENOUGH TO HOLD THEM IN GASEOUS FORM. A CONSEQUENCE OF THIS REASONING IS THAT THE ATMOSPHERE AND HYDROSPHERE MUST BE ENTIRELY OF SECONDARY ORIGIN.

BROWN SUGGESTS THAT  $H_2O$  WAS PROBABLY IN THE FORM OF HYDRATED MINERALS. THIS WOULD HAVE LIMITED TEMPERATURES TO VALUES BELOW WHICH SUCH HYDRATES ARE STABLE.

UREY (1957A) CARRIED OUT A SOMEWHAT SIMILAR ANALYSIS FOR LESS VOLATILE ELEMENTS AND CONFIRMED THE LOW TEMPERATURE SOLID ACCUMULATION HYPOTHESIS. ZINC, CADMIUM, ARSENIC, AND MERCURY ARE RELATIVELY VOLATILE OR FORM VOLATILE COMPOUNDS IN A MIXTURE HAVING COSMIC PROPORTIONS OF THE ELEMENTS. AS NO EVIDENCE FOR THE DEPLETION OF THESE ELEMENTS EXISTS, THEY MUST HAVE ALSO BEEN CAPTURED IN THE FORM OF SOLID PARTICLES.

UREY CONCLUDES THAT TEMPERATURES DURING THE FORMATION OF THE EARTH WERE LESS THAN A FEW HUNDRED DEGREES CENTIGRADE. HOWEVER, TEMPERATURES COULD NOT HAVE BEEN EXTREMELY LOW OR THE NOBLE GASES WOULD HAVE CONDENSED OUT OR HAVE BEEN ADSORBED ON THE SOLID PARTICLES AND THEIR DEPLETION WOULD HAVE BEEN LESS THAN OBSERVED. HENCE, THE TEMPERATURE OF ACCUMULATION SEEMS LIMITED TO A RANGE THAT APPROXIMATES PRESENT SURFACE TEMPERATURE RANGES.

MECHANISM OF PLANET ACCUMULATION. -- THE MAJOR ATTEMPTS TO EXPLAIN THE FORMATION OF THE FOUR INNER OR TERRESTRIAL PLANETS FROM SOLIDS ARE THOSE BY UREY (1957A,B, 1958) AND THE SOVIET SCHOOL (SCHMIDT, 1955, 1958; LEVIN, 1956, 1959). A DISCUSSION OF THE SUBSEQUENT DEVELOPMENT OF METEORITES AFTER ACCUMULATION HAS BEEN GIVEN BY ANDERS AND HIS ASSOCIATES (FISH ET. AL., 1960; ANDERS AND GOLES, 1961). AS THE SURFACE TEMPERATURE, COMPOSITION AND STRUCTURE OF THE GROWING PLANET DEPEND UPON THE ACCUMULATION MECHANISM, THIS PROCESS HAS AN IMPORTANT BEARING UPON THE STRUCTURE OF THE EARTH AND THE PRIMITIVE CRUST.

THE MECHANISM FOR CAUSING MORE OR LESS SPHERICAL, SOLID GRAINS TO AGGREGATE INTO LARGE MASSES HAS BEEN OBSCURE IN ALL ATTEMPTS TO FORM LARGE OBJECTS. A RECENT PROPOSAL (DONN AND SEARS, 1963) POINTS OUT THAT IN THE SOLAR NEBULA CONDENSING PARTICLES SHOULD HAVE INCLUDED A LARGE PROPORTION OF

IRREGULARLY SHAPED GRAINS IN THE FORM OF PLATES, FILAMENTS AND VARIOUS COMBINATIONS. THESE PARTICLES WOULD HAVE THE PROPERTIES ASSOCIATED WITH MINUTE PERFECT CRYSTALS OR WHISKERS, I.E., MECHANICAL STRENGTH AND ELASTICITY SEVERAL ORDERS OF MAGNITUDE GREATER THAN FOR BULK MATERIAL OF THE SAME COMPOSITION. THE SHAPE AND STRENGTH OF THESE GRAINS PROVIDE A MEANS FOR THEM TO COHERE UPON COLLISION. THE RESULTING AGGREGATE WOULD BE A LOW DENSITY POROUS OBJECT AND AN EFFICIENT COLLECTOR OF ALL PARTICLES STRIKING IT.

COMPOSITION OF ACCRETING MATERIAL. - - THE COMPOSITION OF THE PARTICLES FROM WHICH THE EARTH FORMED DEPENDED UPON THE TEMPERATURE OF THE NEBULA AND ITS HISTORY. IN UREY'S TWO-STAGE PROCESS THE FRAGMENTED SOLIDS WERE OF METALLIC OR SILICATE COMPOSITION. IF TEMPERATURES WERE LOW ENOUGH, SOME OF THE VOLATILE COMPONENTS OF THE GAS WOULD HAVE CONDENSED ALSO. A DIFFICULTY WITH THIS SCHEME WHICH UREY (1957A) HAS EMPHASIZED IS THE MECHANISM OF ACCUMULATION OF THE PRIMARY AND SECONDARY OBJECTS INTO THE PLANETS.

IN GENERAL ONE WOULD EXPECT SOLID GRAINS CONDENSING IN THE SOLAR NEBULA TO FORM WHISKERY PARTICLES AS NOTED BY DONN AND SEARS (1963). THE CONDENSATION OF NEBULAR MATERIAL INTO SPHERICAL PARTICLES WOULD HAVE REQUIRED VERY SPECIAL CONDITIONS SUCH AS PROPOSED BY WOOD (1963) FOR THE ORIGIN OF CHONDRULES.



THE WATER IN THE EARTH MAY HAVE RESULTED FROM THE ACCRETION OF ICE GRAINS. THIS WOULD REQUIRE QUITE LOW TEMPERATURES IN THE REGION OF THE EARTH AS PROPOSED BY SCHMIDT (1955) AND OPIK (1962). BROWN (1952) AND LATIMER (1950) PROPOSED THAT THE WATER WAS INCLUDED IN HYDRATED MINERALS. HYDRATED SILICATES WITH THEIR COMPLEX CRYSTAL STRUCTURE COULD FORM FROM A MELT (UREY, 1957A); BUT HARDLY SEEM POSSIBLE FROM THE VAPOR PHASE. THE MEANS OF ACCUMULATION COULD HAVE BEEN AS SIMPLER HYDRATED MOLECULES ( $MgOH$ ,  $NH_4OH$ ), AS ICE PARTICLES, OR AS ADSORBED WATER ON SILICATE GRAINS (UREY, 1952A).

A RATHER THOROUGH DISCUSSION OF CHEMICAL REACTIONS IN THE SOLAR NEBULA HAS BEEN GIVEN BY UREY (1952B). LATIMER (1950) AND EUCKEN (1944) HAVE ALSO CONSIDERED THIS PROBLEM. AT LOW TEMPERATURES, STABLE, NON-VOLATILE GRAINS ARE  $SiO_2$ ;  $Fe_2SiO_4$ ,  $Mg_2SiO_4$ ,  $FeS$ , AND  $Fe_3O_4$  AS WELL AS VARIOUS METALLIC OXIDES. AMONG STABLE VOLATILE CONSTITUENTS ARE  $H_2O$ ,  $NH_3$  AND  $NH_4OH$ . PRESUMABLY THE ORIGINAL GRAINS HAD MUCH THE ABOVE COMPOSITION.

TEMPERATURE OF AN ACCRETING EARTH. - - THE TEMPERATURE OF THE ACCRETING EARTH WAS A DOMINANT FACTOR IN DETERMINING THE COMPOSITION AND STRUCTURE OF THE EARTH AND THE RATE OF ATTAINING ITS ULTIMATE CHARACTERISTICS. A COMPLETE DISCUSSION BECOMES TOO INVOLVED TO INCLUDE HERE, BUT A SURVEY OF ANALYSES OF SUCH TEMPERATURES IS PRESENTED. THE FOLLOWING

FACTORS CONTRIBUTED TO THE HEATING OF THE EARTH AS IT FORMED:  
 (1) TEMPERATURE OF THE SOLAR NEBULA, (2) CONVERSION OF  
 POTENTIAL AND KINETIC ENERGY OF PARTICLES TO HEAT, (3) RELEASE  
 OF CHEMICAL ENERGY OF METASTABLE SPECIES STORED AT LOW  
 TEMPERATURES, (4) WORK DONE IN COMPRESSING MATERIAL FROM  
 INITIAL LOW DENSITY, AND (5) RADIOACTIVE DECAY.

BECAUSE OF THE REQUIREMENT OF A LOW TEMPERATURE  
 ACCUMULATION THE FIRST FACTOR WAS NEGLIGIBLE. INITIALLY  
 PROCESS 2 WAS INEFFICIENT BECAUSE OF LOW IMPACT VELOCITY  
 AND SMALL MASS. AS THE EARTH BECAME LARGER BOTH FACTORS IN  
 2 BECAME MORE EFFECTIVE AND AT SOME STAGE A HIGH SURFACE  
 TEMPERATURE MAY HAVE DEVELOPED. HOWEVER AS THE TERMINAL STAGE  
 APPROACHED WITH THE EARTH NEAR FULL SIZE THE RATE OF GROWTH  
 MUST HAVE DECLINED, APPROACHING ZERO AS ACCUMULATION WAS  
 COMPLETED. THIS FEATURE HAS NOT BEEN TAKEN INTO ACCOUNT IN  
 ANY OF THE TEMPERATURE DETERMINATIONS (TER HAAR AND WERGELAND,  
 1947; BENFIELD, 1950, ETC.) ALTHOUGH IT WAS POINTED OUT BY  
 LEVIN (1957). THE NET EFFECT WAS THAT THERMAL RADIATION  
 COMBINED WITH A SLOW RATE OF CONVERSION OF KINETIC OR POTENTIAL  
 ENERGY TO HEAT WOULD HAVE PREVENTED HIGH SURFACE TEMPERATURES  
 IN THE FINAL STAGES OF FORMATION. LOCAL HIGH TEMPERATURES  
 PROBABLY OCCURRED FROM OCCASIONAL IMPACTS AT THAT STAGE  
 BECAUSE THE ACCUMULATING GRAINS WOULD HAVE AGGREGATED INTO  
 LARGER OBJECTS (OPIK, 1962; DONN AND SEARS, 1963) WHICH WOULD  
 HAVE GENERATED HIGH TEMPERATURES IN THE IMPACT ZONE. UREY'S  
 LUNAR CALCULATION (1952, P. 37) SUGGEST THAT RAPID COOLING

WOULD OCCUR IN THESE LOCALLY HEATED ZONES.

IN A LOW TEMPERATURE NEBULA, CHEMICAL HEATING (PROCESS 3) MAY HAVE BEEN IMPORTANT FOR OBJECTS MUCH SMALLER THAN THE EARTH OR DURING THE INITIAL STAGES OF GROWTH. WHEN THE EARTH WAS NEARLY FULL SIZE CHEMICAL ENERGY WOULD BE RELEASED IMMEDIATELY ON IMPACT AND ITS EFFECT INCLUDED IN THE IMPACT HEATING WHICH WOULD BE SMALL AT THIS STAGE.

PROCESS 4, THE COMPRESSIONAL HEATING, HAS BEEN INVESTIGATED BY LUBIMOVA (1958) AND MAC DONALD (1959) WHOSE RESULTS SHOW THAT THE TEMPERATURE RISE IN THE CENTER WOULD HAVE BEEN ONLY A FEW HUNDRED DEGREES. IN FACT, LUBIMOVA CONCLUDES THAT THE RISE FROM THE COMBINED EFFECTS OF IMPACT, RADIO-ACTIVE HEATING AND COMPRESSION WOULD ONLY HAVE BEEN 1200 DEGREES.

MOST CALCULATIONS OF TEMPERATURES ARISING FROM RADIO-ACTIVE DECAY, PROCESS 5, DON'T APPLY BECAUSE IN THE PRESENT CASE WE ARE CONCERNED WITH AN EARTH OF ESSENTIALLY UNIFORM COMPOSITION. MACDONALD (1959) FOUND FOR SUCH CIRCUMSTANCES THAT MELTING TEMPERATURES FOR A METALLIC PHASE WOULD BE ATTAINED  $0.5$  TO  $2 \times 10^9$  YEARS AFTER AGGREGATION. DIFFERENTIATION OF A CORE WOULD THEN OCCUR A LONG TIME AFTER AGGREGATION. MACDONALD DOES NOT CONSIDER MANTLE-CRUST DIFFERENTIATION BUT IT IS APPARENT THAT IT WOULD TAKE LONGER YET IF IT COULD OCCUR AT ALL.

IN SUMMARY, PRESENT IDEAS CONCERNING THE ORIGIN AND ACCUMULATION PROCESSES ARE FAR FROM DEFINITIVE BUT CERTAIN

CONCLUSIONS CAN BE DRAWN REGARDING THE CHARACTERISTICS OF THE EARTH AT THE TERMINATION OF THE ASTRONOMICAL PHASE OF ITS DEVELOPMENT - THE ACCUMULATION OF ITS COMPLETE MASS. THE EARTH'S COMPOSITION WAS BASICALLY THAT OF A UNIFORM MIXTURE OF RELATIVELY COLD SOLID GRAINS DURING ACCUMULATION. SUCH ACCUMULATION REQUIRES THE SUBSEQUENT HEATING AND SEGREGATION OF THE INTERIOR FOR THE DEVELOPMENT OF THE PRESENT STRUCTURE. BY THE TERMINAL STAGE THE CENTRAL REGION WAS PROBABLY WELL INTO THE PROCESS OF HEATING, ALTHOUGH THE OUTER PORTION MUST STILL HAVE RETAINED ITS PRIMEVAL COMPOSITION AND STRUCTURE. AT THE TIME OF THE EARLIEST DETERMINABLE GEOLOGICAL PROCESSES THE DATA OF THE OLDEST ROCKS SHOWS THAT THE CRUST WAS ALREADY WELL-DIFFERENTIATED. IN THE FOLLOWING SECTIONS WE WILL TRY TO CONNECT THE ASTRONOMICAL WITH THE GEOLOGICAL PHASES BY A FURTHER INTERPRETATION OF THE OLDEST ROCKS.

### THE OLDEST ROCKS

THE OTHER IMPORTANT EVIDENCES THAT MUST BE CONSIDERED IN FORMING AN OPINION ABOUT EARLY CONDITIONS ON THE EARTH ARE THE CHARACTERISTICS OF THE OLDEST ROCKS THAT HAVE BEEN DISCOVERED. THE TWO REGIONS IN WHICH THE ROCKS OF GREATEST MEASURED ANTIQUITY OCCUR ARE SOUTHERN AFRICA AND THE KOLA PENINSULA IN THE USSR. OTHER REGIONS IN WHICH ROCKS OF NEARLY AS GREAT ANTIQUITY HAVE BEEN FOUND ARE IN CENTRAL CANADA, WESTERN UNITED STATES AND WESTERN AUSTRALIA.

SOUTH AFRICA

THE SEBAKWIAN SYSTEM REPRESENTS ONE OF THE OLDEST GROUPS OF ROCKS FOUND IN THE CONTINENT OF AFRICA. THE MICAS FROM A PEGMATITE CUTTING THIS SYSTEM HAVE BEEN DATED BY THE K/AR METHOD (KULP AND POLDERVAART) AT 3.44 B.Y. WHICH MUST BE REGARDED AS A TERMINAL DATE FOR THE SEBAKWIAN. WE MUST EMPHASIZE THAT THIS, AND ALL K/AR DATES TO BE GIVEN, MUST BE CONSIDERED AS MINIMUM DATES OWING TO THE POSSIBILITY OF ESCAPE OF ARGON. ALTHOUGH THE CONCLUSIONS THAT FOLLOW LATER ARE BASED ON THE EXPERIMENTAL VALUES, A REVISION TO GREATER AGES MAY BE JUSTIFIED IN THE FUTURE.

ACCORDING TO THE DESCRIPTION GIVEN BY MACGREGOR (1951), THE SEBAKWIAN ROCKS OUTCROP IN A GENERAL NORTHEAST-SOUTHWEST BELT FROM NEAR MR. DARWIN TO FILABUSI IN EASTERN SOUTHERN RHODESIA. HOWEVER, BASED ON MORE RECENT OBSERVATIONS, POLDERVAART (PERSONAL COMMUNICATION) CONSIDERS THAT ONLY THE ROCKS NEAR GWELO ARE AUTHENTIC SEBAKWIAN. THE GWELO ROCKS INCLUDE HIGH GRADE METAMORPHICS SUCH AS GRANULITES WHOSE ORIGINAL LITHOLOGY IS UNCERTAIN, FELDSPATHIC OR ARKOSIC QUARTZITES AND DIRTY SANDSTONES WITH LENSES OF CONGLOMERATE.

RESTING WITH HIGH ANGULAR UNCONFORMITY ON THE SEBAKWIAN SYSTEM IS THE BULAWAYAN SYSTEM (MACGREGOR, 1941), WHICH CONSISTS OF VOLCANIC GREENSTONES WITH INTERBEDDED ALGAL LIMESTONES AT THE BASE, FOLLOWED BY ARKOSES, GRAYWACKES AND RUSTY CHERTY QUARTZITE. AT THE BIKITA MINE, A PEGMATITE

INTRUSIVE INTO THIS SEQUENCE HAS BEEN DATED AT 2.6 TO 2.8 B.Y. (KULP AND POLDERVAART). ALL OF THESE ROCKS HAVE BEEN COMPLEXLY FOLDED AND METAMORPHOSED AND "INVADED" BY GRANITE BATHOLITHS.

ROCKS OF AN ANTIQUITY EQUIVALENT TO THAT OF THE SEBAKWIAN OCCUR TO THE SOUTH IN SWAZILAND. AS DESCRIBED BY HUNTER (1957), THE BASEMENT COMPLEX DESIGNATED THE SWAZILAND SYSTEM, IS COMPOSED OF COMPLEXLY FOLDED GNEISSES, GRANULITES AND MIGMATITES. THE LOWEST MEMBER OF THE SYSTEM CONTAINS GRANODIORITIC GNEISSES WITH AUGEN OF FELDSPAR AND QUARTZ, AND GRANULITES WITH INTERCALATED QUARTZ SCHISTS. THE ONLY CLEARLY RECOGNIZABLE METASEDIMENTS OCCUR AS LENSES OF QUARTZITE. THE PARAGNEISSES ARE PREDOMINANTLY LIGHT-COLORED, BEING COMPOSED ESSENTIALLY OF QUARTZ AND FELDSPARS. THESE ROCKS GRADE INTO DARKER VARIETIES CONTAINING HORNBLENDE AND PYROXENE. THE NATURE AND COMPOSITION OF THE PRESUMED METASEDIMENTS DESCRIBED HERE AND IN FURTHER DETAIL BY HUNTER SUGGEST STRONGLY AN ORIGIN FROM A SIALIC SOURCE.

THE GRANITES FORMED IN THE METAMORPHISM OF THE SWAZILAND SYSTEM HAVE BEEN DATED TENTATIVELY AT 3.44 B.Y. BY ALLSOPP, ROBERTS, SCHREINER AND HUNTER (1962), WHO USED THE Rb/Sr METHOD ON THE ENTIRE ROCK SAMPLE. THIS DATE MUST ALSO BE REGARDED AS A TERMINAL DATE FOR THE SWAZILAND CYCLE.

DATES FROM ROCKS IN THE BELGIAN CONGO APPROACHING THIS ANTIQUITY HAVE BEEN OBTAINED. AGES OF 3.31 TO 3.43 B.Y. HAVE RESULTED FROM THE METHOD OF MODERN LEAD IN GALENA (HOMES AND CAHEN, 1957). THESE DATES EXTEND THE REGION OF

OLDEST ROCKS NORTHWARD FROM THE EXPOSURES IN SOUTHERN RHODESIA.

THE GREATEST AGE SO FAR OBTAINED WAS DETERMINED FROM A CHARNOKITE GRANITE COLLECTED BY A. POLDERVAART TO THE SOUTH-EAST OF LAKE VICTORIA IN NORTHERN TANGANYIKA (KULP AND POLDERVAART) PERSONAL COMMUNICATIONS). A K/AR AGE OF 3.6 B.Y. WAS DETERMINED AT LAMONT ON THE ROCK WHICH IS DESCRIBED AS OCCURRING ON A HILL REPRESENTING THE REMNANTS OF A THRUST SHEET. AN AGE OF 2.8 B.Y. HAS BEEN OBTAINED FROM THE DODOMAN SCHISTS WHICH OCCUR OVER A LARGE REGION IMMEDIATELY TO THE WEST OF THE GRANITE EXPOSURE.

#### KOLA PENINSULA

THE EARLY PRECAMBRIAN ROCKS IN THE KOLA PENINSULA ARE HIGHLY METAMORPHOSED AND COMPLEXLY FOLDED. ALTHOUGH THE AGE RELATIONS ARE NOT ENTIRELY CLARIFIED, A FAIRLY ORGANIZED PICTURE CAN BE INTERPRETED FROM RECENT SOVIET PUBLICATIONS FROM WHICH THE FOLLOWING DESCRIPTIONS ARE TAKEN (VINOGRADOV AND TUGARINOV, 1961; LAZKO, 1962; PRYATKINA, 1960; MAKIYEVSHII AND NIKOLAYEVA, 1962; POLKANOV AND GERLING, 1959; KHARATONOV, OZHINSKII, VOLODIN AND POLFYEROV, 1961).

THE OLDEST ROCKS ARE THE KATARCHEAN GROUP CONSISTING OF A LOWER BIOTITE GNEISS COMPLEX (KOLA SERIES) AND AN UPPER SERIES COMPOSED OF A VARIETY OF GNEISSES AND AMPHIBOLITES. THIS GROUP IS NOW RECOGNIZED AS BEING OLDER THAN THE LOWER ARCHEAN WITH WHICH IT WAS FORMERLY INCLUDED.

THE LOWER KATARCHEAN IS A GEOSYNCLINE WHICH EXTENDS EASTWARD FROM THE KOLA FJORD (NORTH-NORTHEAST OF MURMANSK). THE MAJOR ROCK TYPES ARE BIOTITE GNEISSES AND GARNETIFEROUS GNEISSES. ACCORDING TO MACIYEVSKII AND NIKOLAYEVA (1962) THE OLDEST BIOTITE GNEISSES, WHICH ARE RESTRICTED TO THE CRESTS OF ANTICLINES, OFTEN CONTAIN DARK-COLORED AMPHIBOLITIC SLATES AND MAGNETITIC QUARTZITES. THE YOUNGER GARNETIFEROUS GNEISSES CONTAIN MORE ALUMINA AND LESS IRON OXIDE AND MAGNESIA.

A  $K/AR_{\text{K}}$  DETERMINATIONS OF 3.44 TO 3.48 B.Y. BY ROLKANOV AND GERLING (1960) WERE MADE ON BIOTITES FROM A BIOTITE GNEISS OF THE KOLA SERIES IN THE VORONYA RIVER VALLEY. KOUVOS AND KULP (1961) HAVE CHECKED AND CONFIRMED THESE DATES. WE AGAIN MUST EMPHASIZE, HOWEVER, THAT THE DATE IS THAT OF THE METAMORPHISM OF THE ROCKS, HENCE IT IS A TERMINAL DATE FOR THE LOWER KATARCHEAN. THE DATES FOR THE TERMINATION OF THE UPPER KATARCHEAN, GIVEN BY POLKANOV AND GERLING (1960) AND PRYATKINA (1960), FALL BETWEEN 2.6 AND 2.8 B.Y.

IT IS ALSO WORTHY OF EMPHASIS THAT THE PRESENCE OF THE QUARTZITE LENSES IN THE LOWER KATARCHEAN OR KOLA SERIES MUST INDICATE THE EXISTENCE OF A SIALIC PARENT ROCK FROM WHICH THE LOWER KATARCHEAN SEDIMENTS WERE DERIVED. THIS WILL BE DISCUSSED FURTHER IN A LATER SECTION.

THE METAMORPHIC ROCK SEQUENCE IN THE SOUTHERN PART OF THE KOLA PENINSULA IS NOT AS CLEARLY DEFINED AS IN THE NORTH. LAZKO (1962) DESCRIBES A KOLA-LIKE WHITE SEA SERIES OF



BIOTITE GNEISSES, BIOTITE-GARNET GNEISSES, AND SILLIMANITE GNEISSES, CONTAINING MANY AMPHIBOLITES AND PYROXENIC SLATES. THESE MAY BE CORRELATIVE WITH SOME PART OF THE KATARCHEAN OF THE NORTHERN KOLA REGION ACCORDING TO MACIYEVSKII AND NIKOLAYEVA (1962).. IN THE KANDALASH BAY SHORE REGION, A BELT OF GRANITIZED GNEISSES CONTAINS AMPHIBOLITES WHICH INCLUDE CARBONATE LENSES. A K/AR DATE OF 3.25 B.Y. ON A GRANITE FROM THE SOUTHERN PART OF THE KOLA PENINSULA IS GIVEN BY POLKANOV AND GERLING (1960). . ALTHOUGH POSITIVE CORRELATIONS HAVE NOT YET BEEN MADE, THIS DATE SUPPORTS THE VIEW THAT THE ROCKS OF THE SOUTHERN PART OF THE KOLA PENINSULA ARE AT LEAST EQUIVALENT TO SOME PART OF THE KATARCHEAN OF THE NORTHERN PORTION OF THE PENINSULA.

#### NORTH AMERICA

ONE OF THE OLDER PARTS OF THE CANADIAN SHIELD IS FOUND ALONG THE WINNIPEG RIVER IN SOUTHEASTERN MANITOBA. THE OLDEST ROCKS, WHICH ARE KNOWN AS THE RICE LAKE SERIES ARE DIVIDED INTO THREE PHASES. (WRIGHT, 1932). THE LOWEST, MANGOTAGAN PHASE, IS COMPOSED OF QUARTZITE, GRAYWACKE, SLATE, CHERT AND CONGLOMERATE IN PART RECRYSTALLIZED INTO GRANITE SCHIST AND GNEISS.

NUMEROUS PEBBLES AND BOULDERS OF GRANITE ARE FOUND IN THE MANGOTAGAN COMGLOMERATE. THE GRANITIC SOURCE FROM WHICH THIS MATERIAL HAS BEEN DERIVED MUST HAVE BEEN EXPOSED DURING THE TIME OF SEDIMENTATION OF MANY OF THE MANGOTAGAN SEDI-

MENTARY UNITS ALTHOUGH NO OUTCROPS OF THE ORIGINAL ROCK HAVE SO FAR BEEN FOUND. IT MUST BE NOTED THAT DAVIES (1956) OFFERED SOME INCONCLUSIVE REASONS TO QUESTION THE CONGLOMERATIC NATURE OF THE MANGOTAGAN CONGLOMERATE, SUGGESTING THE ROUNDED AND ELONGATED GRANITE FRAGMENTS WERE INTRUSIONS INTO AN ORIGINAL SCHIST. UNTIL THE RESULTS OF OUR FIELD STUDY AND LABORATORY ANALYSIS AND DATING OF THIS UNIT IS COMPLETE, WE WILL FOLLOW THE CONGLOMERATIC ORIGIN PROPOSED BY WRIGHT (1932), DERRY (1930) AND APRINGER (1949).

THE RICE LAKE SERIES HAS BEEN INVADED BY PEGMATITES THAT POST-DATE THE METAMORPHISM OF THE SERIES. Rb/Sr AGE DETERMINATIONS (REVIEWED BY GASTIL, 1960) WHICH HAVE BEEN PERFORMED ON LEPIDOLITE FROM THESE PEGMATITES GIVE AN AGE OF ABOUT 2.65 B.Y. WHICH MUST BE CONSIDERED A TERMINAL DATE FOR THE RICE LAKE CYCLE.

THE TIGHTLY FOLDED RICE LAKE FORMATIONS THUS APPEAR TO BE A CORRELATIVE OF THE BULAWAYAN SERIES OF SOUTHERN RHODESIA AND OF THE UPPER KATARCHEAN OF THE KOLA PENINSULA. THE GRANITE BOULDERS IN THE LOWER RICE LAKE CONGLOMERATE MUST HAVE BEEN DERIVED FROM EITHER A STILL OLDER OROGENIC BELT OR A PRIMORDIAL GRANITE SOURCE. IF THE FORMER, THE ROCKS INVOLVED IN THE OROGENIC BELT MIGHT WELL BE CORRELATIVE WITH THE SEBAKWIAN SYSTEM, THE SWAZILAND SYSTEM AND THE KOLA SERIES.

A RECENT STUDY OF THE U/Pb SYSTEM IN ZIRCONS FROM ANCIENT ROCKS OF THE BEARTOOTH MOUNTAINS OF MONTANA WAS MADE BY CATANZARO (1962). THE MAJOR ROCK UNITS IN THE AREA OF QUAD

CREEK, WHERE MANY OF THE SAMPLES WERE TAKEN, OCCUR IN A TIGHTLY FOLDED SYNCLINE. THIS GROUP CONSISTS OF PRECAMBRIAN ; GRANITE GNEISS, MIGMATITE, METASEDIMENTARY ROCKS (PRIMARILY PARAAMPHIBOLITES AND QUARTZITES DERIVED FROM ARENITES, LUTITES AND POSSIBLE CALCILUTITES) AND METAMORPHOSED MAFIC DIKES AND STOCKS (ECKELMANN AND POLDERVAART, 1957). THE AGES, BASED UPON  $Pb^{207} / Pb^{206}$  IN ZIRCONS, RANGE FROM 2.6 TO 3.1 B.Y.

THE ZIRCONS ARE INTERPRETED AS DETRITAL GRAINS THAT HAVE SURVIVED METAMORPHISM BUT HAVE OFTEN HAD SURFACE OVERGROWTHS DURING ONE OR MORE OF THE MAJOR EVENTS THAT AFFECTED THE REGION AT 2.8, 1.8 AND 0.5 BILLION YEARS AGO. IT IS RECOGNIZED THAT THE AGE DETERMINATIONS FROM THE ZIRCONS ARE DISCORDANT AND LOW. DISCUSSIONS BY CATANZARO AND ALSO BY KULP (1962) LEAD TO THIS INTERPRETATION: "THE ISOTOPIC AGES SUGGEST THAT THE ORIGINAL ZIRCONS WERE FORMED AT LEAST 35 HUNDRED MILLION YEARS AGO AND PROBABLY 4 THOUSAND MILLION YEARS AGO, BUT EXPERIENCED EPISODIC LEAD LOSS 2650 MILLION YEARS AGO DURING THE LAST REGIONAL METAMORPHISM WHICH WAS ACCOMPANIED BY PEGMATITE INTRUSION." THIS AGE (2650 M.Y.), WHICH IS BASED ON ISOTOPIC LEAD MEASUREMENTS FROM THE PEGMATITIC MICROCLINE (CATANZARO AND GAST, 1960), IS PRESUMABLY POST-METAMORPHIC BUT RELATED TO THE OROGENY WHICH CULMINATED IN THE METAMORPHIC ROCKS REFERRED TO ABOVE.

IT MUST AGAIN BE NOTED THAT THESE ANCIENT BEARTOOTH METASEDIMENTS CONTAIN ZIRCON GRAINS OF MUCH GREATER ANTIQUITY

THAN THE MATRIX. ALTHOUGH ZIRCON OCCURS IN MOST IGNEOUS ROCKS, IT PREPONDERATES IN GRANITES WHICH SEEMS THE LIKELY SOURCE OF THE SEDIMENTARY ZIRCON. THIS, TOGETHER WITH THE PRESENCE OF METAMORPHOSED QUARTZ SANDSTONES, THE SOURCE OF WHICH HAS NOT YET BEEN DISCOVERED, INDICATE A SIALIC PARENT ROCK.

THE BEARTOOTH METASEDIMENTS IN THE STILLWATER RIVER AREA, ABOUT 25 MILES NORTHWEST OF THE QUAD CREEK REGION HAVE ALSO BEEN THE SUBJECT OF RECENT REINVESTIGATION. THE STILLWATER IGNEOUS COMPLEX, DESCRIBED IN DETAIL BY HESS (1960) IS INTRUDED INTO THE BEARTOOTH GROUP WHICH HAVE BEEN DESCRIBED BY A. POLDERVAART (PERSONAL COMMUNICATION) TO CONSIST OF SOME QUARTZITE AND IRON STONE MEMBERS WITHIN A MAIN MASS OF METAMORPHOSED POTASSIC SHALES. A K/AR DATE ON BIOTITE FROM THE METAMORPHIC AUREOLE BORDERING THE INTRUSION WAS FOUND TO BE 3.2 B.Y. (J. L. KULP, PERSONAL COMMUNICATION). IN ADDITION TO DATING THE INTRUSION, THIS DATE ESTABLISHES AT LEAST A MINIMUM AGE FOR THE DEPOSITION OF THE ORIGINAL BEARTOOTH SEDIMENTS WHOSE COMPOSITION HERE AGAIN IMPLIES AN EARLIER SIALIC SOURCE.

IN THE INVESTIGATION OF ANCIENT ROCK AGES IN NORTHWESTERN WYOMING, TO THE SOUTH OF THE BEARTOOTH RANGE, GILETTI AND GAST (1961) AND BASSETT AND GILETTI (1963) REPORT Rb/Sr AGES UP TO 2.7 B.Y. ON MUSCOVITE FROM PEGMATITES THAT CUT HIGHLY METAMORPHOSED ROCKS. THESE AUTHORS CONCLUDE THAT THESE AGES, WHICH REPRESENT TERMINAL METAMORPHISM OF A SEDIMENTARY SEQUENCE, ARE EXTENSIVE IN WESTERN AND CENTRAL WYOMING. THE

METASEDIMENTS OF QUAD CREEK, NORTHWEST WYOMING AND THE STILLWATER AREA APPEAR TO BE A UNIFORM GEOLOGIC REALM. THE FIRST TWO SEEM TO BE CORRELATIVE WITH THE RICE LAKE, BULAWAYAN AND UPPER KATARCHEAN. THE STILLWATER MAY BE OLDER, POSSIBLY CORRESPONDING TO THE STILL OLDER ROCKS IN AFRICA.

### AUSTRALIA

ACCORDING TO WILSON, COMPSTON, JEFFERY AND RILEY (1960), THE OLDEST ROCKS IN AUSTRALIA SHOW ESSENTIAL UNITY IN STRUCTURE AND AGE IN A REGION OF ABOUT 500,000 SQUARE MILES IN WESTERN AUSTRALIA. ALTHOUGH THE MOST ACCURATELY DATED AREA IS AT BOYA, NEAR PERTH, WHERE THE TOTAL ROCK METHOD ON GRANITE GIVES AN AGE OF 2.7 B.Y. FOR THE EMPLACEMENT OF THE GRANITE, Rb/Sr AND K/Ar AGE DETERMINATIONS OVER THE VAST AREA REFERRED TO ABOVE ALSO GIVE 2.7 B.Y. (WITHIN A 1/4 PER CENT SPREAD) AT MANY LOCALITIES. THIS LATTER AGE WAS DETERMINED ON LITHIUM-BEARING PEGMATITES WHICH INJECT THE KALGOORLIE GREENSTONES AND THUS INDICATE THE DATE OF METAMORPHISM OF THIS WIDESPREAD ROCK SYSTEM. THE GREENSTONES WERE DERIVED FROM BASALTIC AND ANDESITIC LAVAS, PYROCLASTICS, BASIC AND ULTRABASIC INTRUSIONS, BANDED IRON FORMATIONS AND ILL-SORTED CLASTIC SEDIMENTS.

THE GREENSTONES OCCUR IN LONG NARROW BELTS SURROUNDED ON ALL SIDES BY GRANITE OR GRANITE GNEISS WHICH ARE REGIONALLY CONCORDANT WITH THE GREENSTONES. THE GNEISSES, WHICH ARE IN PART AT LEAST, "REMETAMORPHOSED" INTO A COMPLEX CONTAINING CHARNOKITIC ROCKS OF ALL TYPES, ARE CONSIDERED BY WILSON (1958)

TO BE THE OLDEST ROCKS PRESENT, AND TO REPRESENT THE MORE ACID CRUST ON WHICH THE ORIGINAL GREENSTONE SOURCE ROCKS WERE LAID DOWN. NO DATES ON THE ANCIENT GNEISSES HAVE BEEN GIVEN ALTHOUGH AGE DETERMINATIONS ARE PLANNED. AT PRESENT, THEREFORE, ANY TENTATIVE CORRELATION WITH ROCK GROUPS OF GREAT ANTIQUITY ON OTHER CONTINENTS IS DIFFICULT.

ONE OF THE CLASTIC UNITS INCLUDED IN THE GREENSTONES FROM SOUTHERN CROSS HAS MORE RECENTLY BEEN DESCRIBED BY MARSHALL, MAY AND PERRET (1964) TO BE A FINE-GRAINED QUARTZITE CONSISTING OF ANGULAR QUARTZ GRAINS.

#### DIRECT CONCLUSIONS FROM THE GEOLOGIC DATA

THE DATA ON THE OLDEST ROCK SEQUENCES PROVIDE THE BASIS FOR ESTABLISHING CERTAIN LIMITS REGARDING CONDITIONS AND EVENTS IN THE EARLIEST GEOLOGIC PHASE OF EARTH HISTORY. IN THE INTERPRETATION OF THESE DATA CERTAIN ASSUMPTIONS OR GENERALIZATIONS ARE INVOLVED. ALTHOUGH FURTHER STUDY MAY ALTER OR REFUTE SOME OF THE CONCLUSIONS, THE METHOD OF ANALYSIS SEEMS VALID.

IN AFRICA AND THE KOLA PENINSULA THE TERMINAL DATE FOR THE EARLIEST KNOWN GEOSYNCLINE CYCLES IS ABOUT 3.5 B.Y. IN ALL CASES IT IS NECESSARY TO ASSUME A PRECEDING TIME INTERVAL SUFFICIENTLY GREAT TO ACCUMULATE GEOSYNCLINAL PILES AND RAISE THEM TO A HIGH DEGREE OF METAMORPHISM. IT SEEMS POSSIBLE TO ESTIMATE THE LENGTH OF THIS INTERVAL BY COMPARISON WITH THE

INTERVAL OF LATER CYCLES WHOSE TIME LIMITS ARE BETTER KNOWN.

AS NOTED EARLIER, THE NEXT MAJOR DIASTROPHIC EVENTS IN SOUTHERN RHODESIA AND THE NORTHERN KOLA PENINSULA OCCURRED AT ABOUT 2.6 TO 2.8 B.Y. IN VIEW OF THE LONG TIME INTERVAL BETWEEN SUCCESSIVE TERMINAL EVENTS IT SEEMS VERY REASONABLE TO CONCLUDE THAT THE EARLIEST CYCLE CUMINATING AT 3.5 B.Y. MUST HAVE BEGUN AT LEAST 4 BILLION YEARS AGO. THIS ARGUMENT IS GIVEN STRONG SUPPORT IN A LATER SECTION WHICH EMPHASIZES THE PROBABLE SLOW RATE OF EROSION IN AN EARLY GEOLOGIC TIME AS A RESULT OF LOW TEMPERATURE, LOW ATMOSPHERIC WATER VAPOR CONTENT AND ABSENCE OF ORGANIC ACIDS.

THIS LINE OF REASONING LEADS TO THE CONCLUSION THAT SUBAERIAL EROSION, INVOLVING RUNNING WATER, WAS IN OPERATION AT LEAST 4 BILLION YEARS AGO. BECAUSE THESE ESTIMATES ARE BASED IN PART ON THE K/AR METHOD OF ISOTOPIC DATING, THEY MAY BE CONSIDERED MINIMAL OWING TO THE POSSIBLE LOSS OF ARGON AS NOTED EARLIER. IT MAY ALSO BE CONCLUDED THAT AT LEAST A PORTION OF THE CONTINENTAL CRUST UNDERGOING EROSION ABOUT 4 BILLION YEARS AGO CONSISTED OF QUARTZ-BEARING SIALIC ROCK MATERIAL.

THE TIMING OF EVENTS FOR NORTH AMERICA IS NOT AS DEFINITIVE BUT, NEVERTHELESS LEADS TO CONCLUSIONS OF GREAT ANTIQUITY REGARDING THE AGE OF THE FIRST EROSIONAL CYCLE. THE TERMINAL EVENT OF THE FIRST CLEAR-CUT SEDIMENTARY CYCLE IN MANITOBA IS ABOUT 2.6 TO 2.7 B.Y. IF THE GRANITE INCLUSIONS IN THE RICE LAKE CONGLOMERATES ARE CONSIDERED TO BE PRIMORDIAL

CRUST, THE FIRST CYCLE WOULD HAVE BEGUN ABOUT 3.5 BILLION YEARS AGO. IF, HOWEVER, THIS GRANITE REPRESENTS THE CULMINATION OF A PRECEDING GEOSYNCLINAL CYCLE, THAN THE FIRST CYCLE COULD ALSO BE EXTRAPOLATED BACK TO AT LEAST 4 BILLION YEARS. IN THE BEARTOOTH REGION, IF THE ESTIMATED MINIMUM AGES OF 3.5 TO 4.0 B.Y. FOR THE BEARTOOTH ZIRCONS ARE VALID, THEN A SIMILAR HISTORY FOR THIS REGION CAN BE ARGUED, PARTICULARLY IN VIEW OF THE QUARTZ-BEARING SEDIMENTS WHICH MUST CERTAINLY HAVE BEEN DERIVED FROM SIALIC MATERIAL. THE STILLWATER DATE CERTAINLY ESTABLISHES THE EXISTENCE OF A SEDIMENTARY PILE AT 3.2 B.Y. WHICH MAY HAVE BEGUN ABOUT 3.5 B.Y. AS THE STILLWATER SEDIMENTS INDICATE A SIALIC SOURCE THEY MAY REPRESENT THE EROSION OF A PRIMORDIAL GRANITE CRUST OR AN EARLIER CYCLE GRANITIZED MASS.

EVIDENCE FOR AN INITIAL ACID CRUST OVER AT LEAST A LARGE PART OF AUSTRALIA IS ALSO STRONG IN VIEW OF THE GRANITE AND GRANITE GNEISS BASEMENT IN THE WESTERN PART OF THE CONTINENT, AND THE QUARTZITE COMPOSED OF ANGULAR PARTICLES IN THE OVERLYING GREENSTONES. THE LATTER MUST BE GREATER IN AGE THAN 2.7 B.Y., THE TIME OF PEGMATITE INJECTION AND METEMORPHISM. BECAUSE THE GREENSTONES ARE MOSTLY IGNEOUS IN ORIGIN, IT IS DIFFICULT TO ESTIMATE THE TIME OF INITIATION OF THIS SYSTEM AS IS POSSIBLE WITH GEOSYNCLINAL DEPOSITS. CERTAINLY THE REMETAMORPHOSED GNEISSES, DESCRIBED AS THE BASEMENT, ARE CONSIDERABLY OLDER. IF FIRST CYCLE, THEY PROBABLY REPRESENT PRIMEVAL ACID CRUST; IF SECOND CYCLE, THEY MUST REPRESENT



GEOLOGICAL ACTIVITY INVOLVING EROSION OF PREEXISTING ACID ROCKS AT LEAST 3.5 BILLION YEARS AGO, AND POSSIBLY 4.

A SUMMARY OF OUR DIRECT CONCLUSIONS FROM THE GEOLOGIC DATA ARE (1) AT LEAST PARTS OF THREE MAJOR CONTINENTS WERE PRESENT ABOUT 4 BILLION YEARS AGO; (2) QUARTZ-BEARING SIALIC MATERIAL EXISTED IN THESE CONTINENTS WHICH MUST HAVE BEEN LARGER THAN THE AREAS IN WHICH ROCKS OF THIS ANTIQUITY HAVE BEEN FOUND FORTUITOUSLY; (3) SUBAERIAL EROSION BY WATER TRANSPORT WAS ACCUMULATING SEDIMENTS IN GEOSYNCLINAL TROUGHS ABOUT 4 BILLION YEARS AGO; (4) ADEQUATE RELIEF MUST HAVE EXISTED TO INITIATE AND MAINTAIN THIS PROCESS; AND (5) ABOVE-FREEZING TEMPERATURES MUST HAVE PREVAILED OVER AT LEAST PART OF THE EARTH'S SURFACE.

## GEOLOGICAL AND ASTRONOMICAL IMPLICATIONS OF THE OLDEST ROCKS

### SOLAR LUMINOSITY

THE DATA AND INTERPRETATIONS GIVEN ABOVE LEAD TO THE CONCLUSION THAT RUNNING WATER REQUIRED FOR ROCK EROSION AND SEDIMENT TRANSPORT EXISTED AT A NUMBER OF PLACES HAVING A WIDE DISTRIBUTION OVER THE EARTH'S SURFACE. CONSEQUENTLY THE TEMPERATURE OF MUCH OF THE SURFACE ATMOSPHERE MUST HAVE BEEN ABOVE FREEZING FOR MUCH OF THE YEAR. THIS LEADS DIRECTLY TO A CONSIDERATION OF THE SOURCE AND MAINTENANCE OF THE ATMOSPHERIC HEAT ENERGY AND AN EVALUATION OF ASTROPHYSICAL THEORY OF SOLAR EVOLUTION.

THE ULTIMATE SOURCE OF THIS ENERGY IS THE SUN AND THE LEVEL OF THIS ENERGY IS FUNDAMENTALLY DETERMINED BY SOLAR LUMINOSITY, WHICH HAS BEEN SLOWLY INCREASING ACCORDING TO ASTROPHYSICAL THEORY. IF WE CONSIDER THE PRESENT ATMOSPHERE AND NEGLECT THAT PORTION OF THE SOLAR CONSTANT LOST THROUGH REFLECTION BY THE EARTH AND ATMOSPHERE (ABOUT 43 PER CENT), ONLY ONE-FOURTH OF THE INSOLATION IS DIRECTLY ABSORBED BY THE ATMOSPHERE AND THE REMAINING THREE-FOURTHS BY THE EARTH'S SURFACE. THIS RESULTS FROM THE TRANSPARENCY OF THE ATMOSPHERE TO THE VISIBLE SPECTRUM WHICH COMPOSES ABOUT 90 PER CENT OF THE SOLAR CONSTANT. FOR THE MOST PART, THE LOWER ATMOSPHERE IS DIRECTLY HEATED FROM BELOW IN ORDER OF IMPORTANCE BY (1) ABSORPTION OF LONG WAVE (INFRARED) RERADIATION FROM THE EARTH'S SURFACE, (2) RELEASE OF LATENT HEAT OF CONDENSATION FROM WATER ORIGINALLY EVAPORATED THROUGH THE ENERGY OF THE SHORT RADIATION BY THE OCEANS, AND (3) DIRECT CONDUCTION FROM THE SURFACE FOLLOWED BY TURBULENT (CONVECTIVE) TRANSFER.

INFRARED ABSORPTION IN THE ATMOSPHERE IS ACCOMPLISHED CHIEFLY BY WATER VAPOR AND CARBON DIOXIDE WITH THE FORMER BEING MUCH MORE IMPORTANT AT PRESENT IN VIEW OF ITS GREATER ATMOSPHERIC ABUNDANCE AND ITS MUCH MORE EFFECTIVE ABSORPTION OVER A BROAD SPECTRAL RANGE. THE COMPOSITION OF THE ATMOSPHERE THUS PLAYS A VERY IMPORTANT ROLE IN ITS HEAT BUDGET. THIS COMPOSITION MUST BE CONSIDERED FOR THE PRIMITIVE ATMOSPHERE BEFORE SOLAR LUMINOSITY CAN BE DIRECTLY RELATED TO EARLY SURFACE TEMPERATURE CONDITIONS.

WE CAN MAKE A GOOD ESTIMATE OF THE PRESENT GREENHOUSE EFFECT OF THE ATMOSPHERE FROM THE INFRARED ABSORPTION JUST DESCRIBED. THE RADIATION TEMPERATURE OF THE EARTH'S SURFACE IS  $246^{\circ}\text{K}$  FOR A TERRESTRIAL ALBEDO OF 40 PER CENT. AS THE AVERAGE SURFACE TEMPERATURE OF THE ATMOSPHERE IS  $288^{\circ}\text{K}$  (INTERNATIONAL STANDARD ATMOSPHERE), THE PRESENT GREENHOUSE EFFECT OF  $42^{\circ}\text{K}$  IS QUITE SIGNIFICANT.

TO CONSIDER WATER VAPOR FIRST, A RECIPROCAL RELATIONSHIP EXISTS BETWEEN AIR TEMPERATURE AND WATER VAPOR CONTENT. THE TEMPERATURE OF THE AIR DETERMINES THE VAPOR DENSITY OF WATER WHOSE GREENHOUSE EFFECT FURTHER INCREASES THE HEAT BUDGET OF THE ATMOSPHERE. WITH A FAIRLY UNLIMITED OCEANIC SUPPLY AND A GIVEN LUMINOSITY, EQUILIBRIUM TEMPERATURES AND COMPOSITION WILL TEND TO FORM AS AT THE PRESENT TIME. IT SEEMS CLEAR FROM THIS THAT THE WATER VAPOR CONTENT MUST DEPEND FUNDAMENTALLY UPON THE INTENSITY OF INSOLATION.

IF THE OCEANS ACCUMULATED SLOWLY THROUGH EXHALATION FROM THE EARTH'S INTERIOR, AS DISCUSSED BY RUBEY (1951) AND SUPPORTED BY KULP (1951), THEN ITS EARLY SURFACE AREA MUST HAVE BEEN QUITE LIMITED. HUTCHINSON (1954) ALSO ESTIMATES THE PREBIOLOGICAL OCEAN VOLUME TO BE NO MORE THAN 5 TO 10 PER CENT OF THE PRESENT OCEANS. ON THE BASIS OF A PROBABLE SLOW ACCUMULATION OF THE HYDROSPHERE TOGETHER WITH THE DEPENDENCE OF TEMPERATURE ON SOLAR LUMINOSITY, WE MUST REGARD WATER VAPOR AS UNIMPORTANT IN EVALUATING THE TEMPERATURE IN THE PRIMITIVE ATMOSPHERE.

AT PRESENT THERE IS ALSO INCOMPLETE AGREEMENT ABOUT THE COMPOSITION OF THE EARLY ATMOSPHERE AS REGARDS THE OTHER VOLATILES, INCLUDING THOSE WHICH MIGHT STRONGLY AFFECT THE ATMOSPHERIC HEAT BUDGET. UREY (1952) CONSIDERS AN EARLY ATMOSPHERE AS CONSISTING OF WATER VAPOR, HYDROGEN, METHANE AND AMMONIA WITH THE QUANTITIES OF EACH BEING UNCERTAIN. ALTHOUGH METHANE HAS SOME ABSORPTION BANDS IN THE INFRARED, THE INTENSITY AND SPREAD OF THIS ABSORPTION IS VERY SMALL COMPARED TO WATER VAPOR, AND EVEN TO CARBON DIOXIDE. FURTHER, AS DISCUSSED BY HUTCHINSON (1954), OXYGEN, PRODUCED BY PHOTODECOMPOSITION, WOULD HAVE OXIDIZED METHANE TO CARBON DIOXIDE, WHICH IS SUGGESTED AS AN IMPORTANT SOURCE OF THE LATTER. IF EXHALED SLOWLY DURING GEOLOGIC TIME, AS SUGGESTED FOR OTHER VOLATILES, THE CONCENTRATION OF METHANE MAY NEVER HAVE BEEN GREAT. ACCORDING TO THIS CONCEPT OF THE EARLY ATMOSPHERE, CARBON DIOXIDE WOULD HAVE HAD A LOW CONCENTRATION AND THEREFORE WOULD HAVE BEEN OF LITTLE IMPORTANCE IN THE ATMOSPHERIC HEAT BUDGET.

RUBEY (1955) REJECTS UREY'S ESTIMATE OF THE COMPOSITION OF THE EARLY ATMOSPHERE ON THE BASIS OF GEOCHEMICAL OBSERVATIONS AND REASONING, PROPOSING INSTEAD THAT NITROGEN AND CARBON DIOXIDE WERE THE DOMINANT GASES PRESENT. RUBEY EXAMINES TWO PRIMITIVE ATMOSPHERIC MODELS HAVING HIGH AND LOW DENSITIES OF ORIGINAL VOLATILES. HE CONCLUDES FROM THE GEOLOGIC RECORD THAT THE CARBON DIOXIDE CONCENTRATION COULD NOT HAVE BEEN EXCESSIVE, BUT AT LEAST THIS VOLATILE MUST HAVE ACCUMULATED GRADUALLY DURING GEOLOGIC TIME.

AMMONIA IS THE ONLY VOLATILE SUGGESTED FOR A PRIMITIVE ATMOSPHERE THAT IS EFFECTIVE IN THE ABSORPTION OF INFRARED IN THE BAND IMPORTANT IN THE GREENHOUSE EFFECT. HOWEVER, THE HIGH SOLUBILITY OF AMMONIA IN WATER WOULD PREVENT THE ACCUMULATION OF AN AMMONIA ATMOSPHERE SIGNIFICANTLY DENSER THAN THE AQUEOUS CONTENT OF THE PRESENT ATMOSPHERE. PRESUMABLY, THE PRODUCTION OF LARGE QUANTITIES OF AMMONIA WOULD INVOLVE THE SIMULTANEOUS GENERATION OF LARGE QUANTITIES OF WATER INTO WHICH THE AMMONIA WOULD DISSOLVE. THEREFORE A LARGE GREENHOUSE EFFECT FOR THE PRIMITIVE EARTH DUE TO AMMONIA SEEMS UNLIKELY.

THE MOST REASONABLE CONCLUSIONS WE CAN MAKE AT THIS TIME FROM THE OBSERVATIONS AND DEDUCTIONS OF GEOCHEMISTRY ARE THAT THE EARLY ATMOSPHERE WAS PROBABLY NO MORE, AND VERY LIKELY LESS, ABSORBENT IN THE INFRARED REGION THAN THE PRESENT ATMOSPHERE. SURFACE AIR TEMPERATURES MUST THEREFORE HAVE BEEN CONTROLLED PRIMARILY BY THE DIRECT INFLUENCE OF SOLAR LUMINOSITY RATHER THAN THE GREENHOUSE EFFECT. AS SUCH, THE TIME OF EARLIEST DETECTABLE LIQUID WATER ABLE TO CAUSE EROSION AND TRANSPORTATION OF SEDIMENTS (ABOUT 4 BILLION YEARS AGO) ESTABLISHES THE EARLIEST TIME AT WHICH SOLAR LUMINOSITY REACHED A VALUE NECESSARY TO SUSTAIN ABOVE-FREEZING TEMPERATURES.

IN APPLYING THIS CONCLUSION TO ASTROPHYSICAL THEORY OF SOLAR EVOLUTION, WE CAN UTILIZE THE LUMINOSITY CALCULATIONS OF HASELGROVE AND HOYLE (1959) WHICH LEAD TO A SOLAR AGE OF

5.3 B.Y. IN VIEW OF THE UNCERTAINTY OF NUCLEAR DATA AND THEORY AND INITIAL SOLAR COMPOSITION, HOYLE (1960) HAS ESTIMATED THE UNCERTAINTY IN SOLAR LUMINOSITY CALCULATIONS TO BE ABOUT 25 PER CENT. THE GEOLOGIC RESULTS MAY THUS BE OF CONSIDERABLE VALUE IN ESTABLISHING PERMISSIBLE VALUES FOR THESE CALCULATIONS.

TABLE 1, WHICH HAS BEEN DEVELOPED FROM THE AGE CALCULATIONS OF HASELGROVE AND HOYLE, SHOWS A TIME SCALE OF SOLAR EVOLUTION AND RESULTING TERRESTRIAL SURFACE TEMPERATURES ACCORDING TO A CHOICE OF INITIAL CONDITIONS. TIME BEFORE THE PRESENT IS SHOWN IN THE FIRST COLUMN, THE RATIO OF PAST TO PRESENT SOLAR LUMINOSITIES IN THE SECOND COLUMN, THE RATIO OF PAST TO PRESENT BLACK BODY TEMPERATURES IN THE THIRD COLUMN (BASED ON THE FOURTH ROOT OF THE LUMINOSITY) AND THREE SETS OF VALUES OF RESULTING SURFACE AIR TEMPERATURES IN THE LAST THREE COLUMNS.

IN THE COLUMN HEADED  $T_1$ , THE RATIO  $T/T_1$  IS APPLIED TO THE PRESENT AVERAGE SURFACE AIR TEMPERATURE OF  $288^{\circ}\text{K}$ . BECAUSE STUDIES OF CENOZOIC CLIMATE INDICATE A SLOW COOLING WHICH CULMINATED IN THE PLEISTOCENE ICE AGE, PRECEDED BY A WARMER AND MORE EQUABLE GLOBEL CLIMATE, IT MAY BE MORE CORRECT TO USE AN ESTIMATED PRE-LATE CENOZOIC AVERAGE OF  $295^{\circ}\text{K}$ . COLUMN  $T_2$  IS BASED ON THIS VALUE. AS NOTED EARLIER, THE PRESENT RADIATIVE EQUILIBRIUM TEMPERATURE OF THE EARTH (WHICH OMITTS THE PRESENT GREENHOUSE EFFECT) IS  $246^{\circ}\text{K}$ . COLUMN  $T_3$  INDICATES PAST TEMPERATURES BASED ON THIS VALUE..

IF TERRESTRIAL SURFACE TEMPERATURES CROSSED THE FREEZING THRESHOLD 4 BILLION YEARS AGO, THE VALUES IN COLUMN  $T_2$  SEEM TO GIVE THE MOST COMPATIBLE FIT BETWEEN OBSERVATION AND THEORY. WE MUST EMPHASIZE THAT THE ASSUMPTIONS INVOLVED IN DETERMINING  $T_2$  ARE THE MOST FAVORABLE FOR PRODUCING AN EARLY CROSSING OF THE FREEZING THRESHOLD. AS A CONSEQUENCE OF THE FLATNESS OF THE LUMINOSITY CURVE IN FIGURE 2, THE CHANGE IN A BILLION YEARS IS ONLY 3 DEGREES SO THAT THE THEORETICAL RESOLUTION OF THE TIME - TEMPERATURE POINTS IS RATHER COARSE. SMALL CHANGES IN THE THEORETICAL  $L/L_0$  CAN SHIFT THE FREEZING THRESHOLD OVER A LONG TIME INTERVAL. ACCORDING TO COLUMN  $T_1$  (BASED ON PRESENT TEMPERATURES) THE FREEZING POINT WOULD NOT HAVE BEEN CROSSED UNTIL ABOUT 2 BILLION YEARS AGO. ALTHOUGH THE DATA IN COLUMN  $T_3$  DO NOT APPLY DIRECTLY TO RECENT AIR TEMPERATURES, WHICH, AS NOTED EARLIER, ARE CONTROLLED BY A STRONG GREENHOUSE EFFECT, THEY MIGHT VERY WELL APPLY TO THE VERY EARLY ATMOSPHERE. THE RESULTING GREENHOUSE EFFECT COULD HAVE BEEN CONSIDERABLY LESS THAN THAT OF THE PRESENT. IT MAY THEREFORE BE REASONABLE TO TRACE THE SURFACE AIR TEMPERATURE CURVE FROM THE LOWER PART OF COLUMN  $T_3$  TO THE UPPER PART OF COLUMN  $T_2$  AS THE GREENHOUSE EFFECT BECAME MORE IMPORTANT AT WHICH TIME A STEEPENING OF THE TEMPERATURE CURVE WOULD OCCUR.

BEFORE EVALUATING THESE TEMPERATURE RELATIONS FURTHER, ANOTHER IMPORTANT CONSIDERATION MUST BE EXAMINED. IT WAS NOTED PREVIOUSLY THAT THE CURRENT RADIATION TEMPERATURE OF  $246^{\circ}$  K

IS BASED ON AN ALBEDO OF 40 PER CENT. HOWEVER, IF THE EARLY TEMPERATURES WERE SUBFREEZING, AS INDICATED BY PRESENT ASTROPHYSICAL THEORY, THEN A CONSIDERABLE TERRESTRIAL FROST COATING MUST HAVE EXISTED, COMPARABLE TO THE PROBABLE FROST COATING RESPONSIBLE FOR THE MARTIAN POLAR CAP. SUCH A COATING REQUIRES A VERY MINUTE AMOUNT OF WATER AND WOULD HAVE <sup>RAISED</sup> ~~LOWERED~~ THE ALBEDO <sup>ABOVE</sup> ~~BELOW~~ 40 PER CENT RESULTING IN LOWER EARLY TEMPERATURES IN EACH OF THE LAST THREE COLUMNS.

THE IMPORTANCE OF A HIGHLY REFLECTING PRIMITIVE FROST COATING IS STRONGLY EMPHASIZED FROM RECENT THEORETICAL AND EMPIRICAL METEOROLOGICAL OBSERVATIONS. FOR AN ATMOSPHERE TRANSPARENT TO INCIDENT RADIATION, BUDYKO (1962) HAS CALCULATED THAT A SNOW AND ICE COVER OVER THE ENTIRE EARTH FOR A SHORT PERIOD WOULD DECREASE THE MEAN TEMPERATURE BY ABOUT 100<sup>0</sup> C. HIS WORK SUGGESTS THAT THE PRESENT STRONG CONTRAST IN ZONAL TEMPERATURES BETWEEN LOW AND HIGH LATITUDES IS THE RESULT OF REFLECTION FROM THE ICE COVER IN BOTH POLAR REGIONS.



TABLE 1.  
 VARIATION IN SOLAR LUMINOSITY AND RELATED  
 TERRESTRIAL SURFACE AIR TEMPERATURES

TIME B.Y.	$\frac{L}{L_0}$	$\frac{I}{I_0}$	SURFACE AIR TEMPERATURE °K		
			T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>
0	1	1	288	295	246
-1.5	.89	.97	279	286	239
-3.0	.80	.95	272	279	233
-4.0	.74	.93	267	273	288
-4.5	.72	.92	265	271	226

ON A MORE EMPIRICAL BASIS, NAMIAS (1963) SHOWED THAT TEMPERATURES OVER CENTRAL UNITED STATES WERE AS MUCH AS  $6^{\circ}\text{C}$  BELOW EXPECTED VALUES AS A CONSEQUENCE OF THE ADDITIONAL REFLECTION FROM SOMEWHAT EXTENDED SNOW COVER IN THIS REGION FROM MID-FEBRUARY TO MID-MARCH 1960. IN A VERY SIMILAR INVESTIGATION, ADEM (1964) CONSIDERED THE EFFECTS OF THE SNOW COVER OF DECEMBER 1962 WHICH EXTENDED SEVERAL DEGREES FARTHER SOUTH OF THE NORMAL COVERAGE FOR NORTHERN UNITED STATES AND LARGE PARTS OF EUROPE AND ASIA. OBSERVED DEPARTURES OF TEMPERATURE FROM NORMAL FOR JANUARY 1963 REACHED  $6^{\circ}\text{C}$  AND  $10^{\circ}\text{C}$  BELOW EXPECTED VALUES FOR NORTH AMERICA AND EURASIA, RESPECTIVELY.

ALTHOUGH IT SEEMS CERTAIN TO US THAT A PRIMITIVE FROST COATING EXISTED, THE TIME WOULD DEPEND UPON THE RATE OF FORMATION OF THE ATMOSPHERE AND HYDROSPHERE AS WELL AS ON SOLAR LUMINOSITY. IF THE ATMOSPHERE GREW SLOWLY, A HIGHER THAN PREDICTED LUMINOSITY WOULD HAVE BEEN REQUIRED TO PRODUCE ABOVE-FREEZING TEMPERATURES ON THE PRIMITIVE EARTH. WE CANNOT DO MORE THAN TOUCH ON THE PROBLEM OF THE FROST COATING AT PRESENT. TEMPERATURES WOULD CERTAINLY RISE DISCONTINUOUSLY AT THE TIME THE FROST DISAPPEARED.

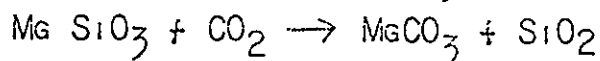
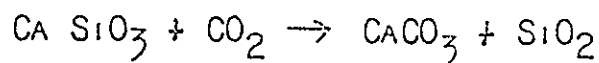
ALTHOUGH THERE IS, OF COURSE, MUCH UNCERTAINTY IN THE GEOLOGIC INTERPRETATIONS OF THE AGE AND COMPOSITION OF THE EARLIEST ROCKS AND THE IMPLIED GEOLOGIC PROCESSES DESCRIBED EARLIER, IT APPEARS THAT SOMEWHAT WARMER CONDITIONS PROBABLY EXISTED 4 B.Y. AGO THAN CURRENT THEORY INDICATES. IF THE

INTERPRETATIONS ARE VALID, ALTERNATIVE HYPOTHESES AFFECTING EARLY TEMPERATURE MUST BE CONSIDERED. 1. THE COMPOSITION OF THE PRIMITIVE ATMOSPHERE MAY HAVE BEEN SUCH AS TO PRODUCE A MUCH GREATER GREENHOUSE EFFECT THAN THE PRESENT, USED IN TABLE 1. AS DISCUSSED ABOVE, WE HAVE REJECTED THIS POSSIBILITY BASED ON CURRENT INFORMATION. 2. THE ZERO AGE OF THE SUN MAY BE GREATER THAN THAT USED IN CURRENT ASTROPHYSICAL CALCULATIONS, AS SUGGESTED EARLIER, IN WHICH CASE THE EARTH MAY ALSO BE OLDER THAN 4.5 B.Y. 3. THE MODEL OF SOLAR COMPOSITION MAY REQUIRE SOME MODIFICATION TO PERMIT HIGHER LUMINOSITIES THAN THE VALUES IN TABLE 1.

#### RATES OF EROSION

THE DATA AND DEDUCTIONS GIVEN ABOVE ALL LEAD TO THE CONCLUSION THAT RATES OF WEATHERING AND EROSION DURING THE EARLY PERIOD OF EARTH HISTORY MUST HAVE BEEN DISTINCTLY SLOWER THAN AT PRESENT. ACCORDING TO THE CURRENT ASTROPHYSICAL THEORY DESCRIBED, TERRESTRIAL SURFACE TEMPERATURES WERE SIGNIFICANTLY LOWER ABOUT 4 BILLION YEARS AGO THAN THEY ARE AT PRESENT. IT IS ALSO LIKELY THAT FOR A LONG TIME, RUNNING WATER MAY ONLY HAVE EXISTED DURING THE SUMMER SEASONS. HENCE, BOTH CHEMICAL AND MECHANICAL WEATHERING IN ADDITION TO WATER EROSION AND TRANSPORTATION WOULD HAVE OPERATED RELATIVELY SLOWLY.

IN ADDITION TO THE TEMPERATURE EFFECT, THE COMPOSITION OF THE ATMOSPHERE, WHICH WAS SO DIFFERENT FROM THAT OF THE PRESENT, WOULD HAVE ALSO ACTED TO SLOW THE RATES OF WEATHERING AND EROSION. OWING TO THE PROBABLE ABSENCE OR LOW ATMOSPHERIC DENSITY OF WATER VAPOR, OXYGEN, AND CARBON DIOXIDE REFERRED TO EARLIER, ROCK DECOMPOSITION MUST CERTAINLY HAVE BEEN VERY RETARDED IN COMPARISON TO THE CURRENT ACTIVITY OF THE HYDRATION, OXIDATION, AND CARBONATION PROCESSES. THE IMPORTANCE OF THE LATTER HAS RECENTLY BEEN STRESSED IN THE IMPORTANT EQUILIBRIUM REACTION DESCRIBED BY UREY (1952) AS FOLLOWS:



FURTHER, RUBEY (1951, 1955) AND TUREKIAN (1959) HAVE EMPHASIZED THE IMPORTANCE OF THE PRESENCE OF ORGANIC ACIDS IN THE WEATHERING OF SILICATES. THEY POINT OUT THE SLOWNESS OF THE DECOMPOSITION PROCESSES REFERRED TO ABOVE IF SUCH MINERALS ARE IN CONTACT WITH RELATIVELY PURE WATER. THUS WHEN ALL OF THESE FACTORS - THE PROBABLE LOW TEMPERATURE, THE EFFECTS OF <sup>ATMOSPHERIC</sup> COMPOSITION ON ROCK WEATHERING AND THE LACK OF ORGANIC ACIDS EARLY IN EARTH HISTORY - ARE TAKEN TOGETHER, IT SEEMS AN INESCAPABLE CONCLUSION THAT EARLY WEATHERING AND EROSIONAL PROCESSES MUST HAVE BEEN RELATIVELY SLOW, AND MUST HAVE INCREASED IN TEMPO DURING GEOLOGIC TIME. THIS REASONING HAS LED IN PART TO THE ESTIMATE OF 0.5 B.Y. FOR THE DURATION OF THE EARLIEST GEOSYNCLINAL CYCLES, REFERRED TO IN AN EARLIER

SECTION, AND ALSO LEADS TO THE CONCLUSION THAT THE DURATION OF INDIVIDUAL GEOSYNCLINAL CYCLES SHOULD HAVE DECREASED WITH TIME.

### FORMATION OF THE CONTINENTS

ALL OF THE DIRECT CONCLUSIONS FROM THE OLDEST ROCKS LEAD DIRECTLY TO A CONSIDERATION OF THE MECHANISM OF FORMATION OF THE EARTH'S CONTINENTAL CRUST. IT WOULD SEEM THAT THE PRESENCE OF EARLY CONTINENTAL PLATFORMS MUST HAVE BEEN THE PRODUCT OF A LOW DENSITY CRUST APPROXIMATING THE COMPOSITION OF GRANITE JUST AS IS TRUE OF THE PRESENT CONTINENTS. THIS LEADS DIRECTLY TO THE AGE-OLD QUESTION OF HOW THESE EARLY GRANITIC CONTINENTAL MASSES ORIGINATED. ALSO, HOW DIFFERENT WERE THEY FROM THE PRESENT CONTINENTS, WHICH HAVE A VOLUME OF ABOUT  $6 \times 10^9 \text{ km}^3$  AND A MASS OF ABOUT  $1.7 \times 10^{22} \text{ kg}$ , 95 PER CENT OF WHICH ARE COMPOSED, EXCLUSIVE OF SEDIMENTS, OF GRANITES AND GRANODIORITES OR THEIR METAMORPHIC DERIVATIVES.

IT IS COMMONLY HELD (E.G., BARTH, 1962, P. 352) THAT "MOST CONTINENTAL ROCKS ARE SIMPLY RECYCLED, MODIFIED SEDIMENTS." AND WE NOW SEE EVIDENCE FOR THE EXISTENCE OF GRANITIC CONTINENTAL MATERIAL PRIOR TO THE EARLIEST RECOGNIZABLE SEDIMENTARY CYCLE. THE MAJOR PROBLEM IN THIS CONNECTION IS WHETHER THE GRANITE WAS SECONDARY, HAVING BEEN DERIVED BY DIFFERENTIATION OR GRANITIZATION, OR WHETHER THIS GRANITE WAS IN A SENSE AN ORIGINAL PART OF THE EARTH'S CRUST.

CLOSELY INVOLVED WITH THIS PROBLEM IS THE TIME SCALE AVAILABLE FOR PRIMEVAL TERRESTRIAL PROCESSES. THE MOST FUNDAMENTAL INFORMATION RELATED TO THE TIME SCALE COMES FROM STUDIES ON THE THERMAL HISTORY OF THE EARTH. MACDONALD'S COMPREHENSIVE STUDY (1959) CONSIDERS A LARGE NUMBER OF MODELS WHICH INCLUDE A SPREAD OF INITIAL TEMPERATURES AND A DIFFERENT DISTRIBUTION OF HEAT SOURCES, ALL FOR AN EARTH OF CHONDRITIC COMPOSITION. OF PARTICULAR INTEREST HERE IS HIS MODEL 14 USING AN INITIALLY HOMOGENEOUS EARTH WITH A UNIFORM TEMPERATURE DISTRIBUTION OF  $1300^{\circ}\text{C}$  AFTER ACCUMULATION. THE DISCUSSION GIVEN EARLIER ON THE ORIGIN OF THE EARTH SUGGESTS A MODEL SIMILAR TO THIS BUT PROBABLY AT A LOWER TEMPERATURE. IN ANY CASE, AS WE DISCUSSED, THE SURFACE MUST HAVE BEEN WELL BELOW THE MELTING POINT.

MACDONALD FINDS, EVEN FOR THE HIGH INITIAL TEMPERATURE OF MODEL 14, THAT  $10^9$  YEARS WOULD BE REQUIRED TO REACH THE MELTING POINT OF THE METALLIC PHASE. THE MANTLE TEMPERATURE WOULD NEVER EXCEED THE MELTING POINT OF SILICATES DURING THIS TIME. ACCORDING TO THESE RESULTS, THE SEPARATION OF THE EARTH INTO CORE AND MANTLE WOULD HARDLY HAVE BEGUN BY A BILLION YEARS AFTER FORMATION. ELSASSER (1963, p. 2) NOTES THAT THE SEPARATION OF THE IRON WOULD NOT OCCUR UNTIL THE SILICATE MATRIX BECOMES SUFFICIENTLY SOFT AS ITS TEMPERATURE APPROACHES THE MELTING POINT. MACDONALD'S CALCULATIONS (FIG. 2) SHOW THAT BELOW 1000 KM THE TEMPERATURE AFTER

A BILLION YEARS IS ABOUT 1500° C BELOW THE SILICATE MELTING POINT. ALTHOUGH THE UPPER 500 KM REMAINED AT ABOUT A CONSTANT TEMPERATURE, THAT OF THE DEEPER PORTION ARE SHOWN TO HAVE BEEN WARMING NEARLY UNIFORMLY.

THE THERMAL HISTORY OF THE EARTH DEVELOPED BY LUBIMOVA (1958) IS ESSENTIALLY IN AGREEMENT WITH THE SOMEWHAT MORE COMPREHENSIVE TREATMENT OF MACDONALD. THE SEPARATION OF THE EARTH INTO A METALLIC CORE AND SILICATE MANTLE MUST BE CONCLUDED TO HAVE BEEN A SLOW PROCESS BASED UPON THE ARGUMENTS AND CONCLUSIONS GIVEN HERE. SEGREGATION IN THE UPPER MANTLE WOULD ALSO BE DELAYED UNTIL ABOUT A BILLION YEARS AFTER ACCUMULATION.

IN THE LIGHT OF THE DATA AND CONCLUSIONS GIVEN SO FAR, WE WILL NOW EXAMINE MECHANISMS WHICH HAVE BEEN PROPOSED FOR THE DEVELOPMENT OF THE CONTINENTS.

1. THE GENERATION OF SECONDARY GRANITE BY THE EXTREME DIFFERENTIATION OF A BASALTIC MAGMA PRESENTS SEVERAL PROBLEMS. FIRST, SUCH A BASALTIC MAGMA CAN DEVELOP ONLY ABOUT FIVE PER CENT OF GRANITE. WE DO NOT FIND THE ROCKS THAT WOULD REPRESENT THE REMAINING 95 PER CENT IN THE REGIONS WHERE GRANITES ARE PREVALENT. SECOND, THE RESIDUAL DIFFERENTIATES OF MOST ROCKS ARE RETAINED WITHIN THEIR MASSES RATHER THAN BEING EXCLUDED TO FORM A GRANITE BODY. BARTH (1962, P. 121-125) DISCUSSES THIS PROBLEM FURTHER AND EXPRESSES THE DIFFICULTY INVOLVED IN THE DERIVATION OF THE GREAT BULK OF GRANITE BY DIFFERENTIATION OF BASALTIC MAGMA.

METASOMATIC GRANITIZATION HAS BEEN CALLED UPON TO EXPLAIN THE ORIGIN OF GRANITES BY MANY AUTHORS (SUMMARIZED BY BARTH, <sup>1962</sup>~~1961~~, P. 349-357). THE MECHANISM PROPOSED INVOLVES THE UPWARD MIGRATION OF K, NA, AL, AND SI AND THE DOWNWARD MIGRATION OF CA, MG, AND FE. WE DO NOT SEE HOW THERE COULD HAVE BEEN ENOUGH TIME FOR THIS PROCESS TO HAVE GENERATED THE PRIMORDIAL CONTINENTAL MASSES BETWEEN THE TIMES OF AGGREGATION OF THE EARTH AND OF THE EARLIEST DEMONSTRABLE GEOSYNCLINAL CYCLE ESPECIALLY IN VIEW OF THE TIME SCALE DEVELOPED FROM THE THERMAL HISTORY. THIS IS SUPPORTED BY THE GEOLOGIC DATA FROM SOUTHEASTERN AFRICA WHICH INDICATES THE PRESENCE OF A RELATIVELY LARGE AMOUNT OF GRANITIC MATERIAL DURING THE EARLIEST SEDIMENTARY CYCLE. IT THEREFORE SEEMS HARD TO ESCAPE THE CONCLUSION THAT A SUBSTANTIAL PRIMORDIAL CONTINENTAL CRUST OF GRANITIC COMPOSITION EXISTED IN AT LEAST THE REGIONS DESCRIBED AND THAT THIS CRUST PROVIDED MUCH OF THE SOURCE MATERIAL FOR EARLIEST EROSION.

FURTHER, THE CONCLUSIONS OF RUBEY (1951) AND KULP (1951), THAT THE HYDROSPHERE AND PART OR ALL OF THE ATMOSPHERE ACCUMULATED SLOWLY AND CONTINUOUSLY DURING GEOLOGIC TIME, TEND TO REFUTE THE POSSIBILITY OF A FAIRLY RAPID SEPARATION OF SIALIC COMPONENTS FROM THE MANTLE TO FORM THE EARLY CONTINENTS. IF THE VOLATILES WERE RELEASED FROM THE INTERIOR SLOWLY, THE FAST RISING OF THE MINERAL CONSTITUENTS REQUIRED FOR CONTINENTAL FORMATION WOULD HARDLY HAVE BEEN POSSIBLE.



ENGLE (1963) HAS REWORKED SOMEWHAT THE CONCEPT OF CONTINENTAL GROWTH BY ACCRETION THROUGH THE DEVELOPMENT OF GRANITIC MATERIAL IN OROGENIC PROCESSES WITHIN ISLAND ARCS. IT SEEMS TO US THAT THE INSTABILITY RELATED TO GEOSYNCLINES AND ISLAND ARCS ARE THE RESULTS OF THE PRESENCE OF CONTINENTS, RATHER THAN THE CAUSE OF THEM AND THAT SIALIC INTRUSIVES AND EXTRUSIVES WITHIN MODERN AND ANCIENT ARC COMPLEXES REPRESENT IN LARGE PART AT LEAST, THE RECYCLING OF MATERIAL ALREADY PRESENT IN THE MARGINS OF CONTINENTAL BLOCKS. THE ANDESITE ZONE MAY SIMPLY REPRESENT THE REGION OF MIXED CONTINENTAL AND OCEANIC MATERIAL. IF WE TRY TO VISUALIZE THE PRIMITIVE EARTH BEFORE THE DEVELOPMENT OF SIALIC MATERIAL, IT IS DIFFICULT FOR US TO IMAGINE THE DEVELOPMENT OF GEOSYNCLINAL PILES WITHOUT THE PRESENCE OF BLOCKS OF SIGNIFICANT RELIEF FROM ORIGINAL DIFFERENCES IN DENSITY.

2. THE CONVECTIONAL PROCESS INVOLVES THE CELLULAR MOTION OF THE MANTLE RESULTING IN THE ACCUMULATION OF A GRANITIC DIFFERENTIATE INTO LOCALIZED MASSES AT THE EARTH'S SURFACE. HILLS (1947) VISUALIZED THIS AS OCCURRING FROM AN ORIGINALLY UNIFORM SURFACE SCUM OF SIALIC COMPOSITION. THIS SEEMS MORE READILY EXPLAINABLE UNDER THE CONDITION OF AN ORIGINAL MOLTEN EARTH THAN UNDER THE CONDITIONS OF COLD ACCUMULATION STRESSED IN THIS REPORT.

CONVECTION WITHIN THE HOT MANTLE HAS BEEN PROPOSED AS AN EXPLANATION OF THE CONTINENTS BY VENNING-MEINEZ (1945) AND HAS BEEN ELABORATED BY HIMSELF AND OTHERS. UREY (1952)

SUGGESTS THAT CONTINUOUS SEGREGATION OF METAL AND SILICATE PHASES MAY SUPPLY ENERGY FOR CONVECTION THROUGH THE GRAVITATIONAL ENERGY RELEASED IN BUILDING THE METALLIC CORE. HOWEVER, THE EXISTENCE OF VISCOUS FLOW IN THE MANTLE BASIC TO ANY CONVECTIVE PROCESS HAS BEEN QUESTIONED BY JEFFREYS (1959), AND MORE RECENTLY BY MACDONALD (1963) AND KNOPOFF (1964).

ON THE BASIS OF THE KNOWN THERMAL GRADIENT<sup>D</sup> THE ESTIMATED RATE OF SURFACE CREEP FROM CONVECTION HAS A SPREAD OVER AN ORDER OF MAGNITUDE FROM ABOUT 2.5 MM TO 2 CM PER YEAR (SCHEIDEGGER, 1958; DIETZ, 1961). IN THE PACIFIC OCEAN THIS WOULD MEAN, FOR THE MAXIMUM VALUE, THAT THE CRUST COULD HAVE BEEN DISPLACED FROM THE CENTER OF THE OCEAN TO THE SHORES OF THE AMERICAS AND ASIA (ABOUT ONE-QUARTER CYCLE OF THE CONVECTION CELL) SINCE EARLY MESOZOIC. FOUR TO FIVE COMPLETE CYCLES COULD HAVE OCCURRED SINCE 4.5 B.Y. AGO, THE ESTIMATED AGE OF THE EARTH'S CRUST, IF THE RATE HAS BEEN FAIRLY CONSTANT.

DIFFERENTIATION IN THE EARTH WAS CERTAINLY AN INEFFICIENT PROCESS. IF WE ASSUME ONLY ONE CYCLE WAS SUFFICIENT, THE ACCUMULATION OF A CONTINENTAL CRUST WOULD HAVE TAKEN ABOUT A BILLION YEARS AT THE ABOVE RATE. TO THIS MUST BE ADDED THE TIME TO HEAT THE EARTH SUFFICIENTLY FOR CONVECTION TO OCCUR. ACCORDING TO THE RESULTS OF BOTH MACDONALD AND LUBIMOVA GIVEN ABOVE, THE THERMAL GRADIENT OF THE MANTLE HAS BEEN STEEPENING WITH TIME, SO THAT PRESENT CONVECTION, IF OCCURRING, COULD HARDLY HAVE BEGUN UNTIL ABOUT A BILLION YEARS AFTER THE EARTH ACCUMULATED. CONVECTION DOES NOT SEEM THEREFORE TO

BE A VALID MECHANISM FOR THE ACCUMULATION OF THE CONTINENTS. EVIDENCE PRESENTED IN THE SECTION ON SOLAR LUMINOSITY LEADS TO A POSSIBLE INTERPRETATION OF A MUCH GREATER AGE FOR THE SUN, AND CONSEQUENTLY OF THE EARTH. IF TRUE, A LONGER TIME INTERVAL WOULD BECOME AVAILABLE FOR THE INITIAL WARMING OF THE INTERIOR.

IN ADDITION TO THE ARGUMENTS ABOVE, WE THEREFORE DO NOT SEE HOW DIFFERENTIATION OR METASOMATIC GRANITIZATION OR CONVECTION COULD HAVE PRODUCED DISCRETE CONTINENTAL MASSES WITHIN THE REQUIRED TIME LIMITS DESPITE RECENT PROPOSALS BY ENGLE (1963) AND MACDONALD (1963). TO ACCOMPLISH THIS WITHIN THE CURRENTLY ACCEPTED AGE OF THE EARTH OF 4.5 B.Y. WE ARE LED INTO THE PROBLEM OF THE ACCUMULATION OF THIS GRANITIC CRUST BY SOME MECHANISM OTHER THAN BY GEOLOGIC PROCESSES. THE ONLY OTHER MECHANISM THAT SEEMS WORTH CONSIDERING AT THIS TIME IS THE IMPACT OF CONTINENTAL-SIZED SIALIC BODIES.

3. THE ORIGIN OF THE CONTINENTS FROM THE IMPACT OF ONE OR MORE CONTINENT-SIZE BODIES OF LOW DENSITY WOULD AVOID MANY OF THE PROBLEMS ARISING FROM THEIR ORIGIN BY DIFFERENTIATION OF ORIGINAL TERRESTRIAL MATERIAL. IF THE VOLUME OF THE SIALIC CONTINENTS IS TAKEN AS  $6 \times 10^9 \text{ km}^3$  (30 KM IN THICKNESS;  $208 \times 10^6 \text{ km}^2$  IN AREA), THE RADIUS OF THE EQUIVALENT SINGLE BODY IS ABOUT  $1.13 \times 10^3 \text{ km}$ . THE PRESENT DISTRIBUTION OF THE CONTINENTS SUGGESTS THAT IF SUCH AN ORIGIN OCCURRED, IT WAS MORE LIKELY FROM SEVERAL LARGE BODIES, WITH THE LARGER CONTINENTS RESULTING FROM AN OVERLAPPING

EFFECT. AUSTRALIA AND ANTARCTICA WOULD THUS REQUIRE THE INFALL OF BODIES WITH DIMENSIONS OF ABOUT THE LARGEST OF THE ASTEROIDS, CERES, WHICH HAS A RADIUS OF 370 KM.

IN CONSIDERING THIS MECHANISM OF CONTINENTAL ORIGIN, HOWELL (1959) ADVANCED AS OBJECTIONS THE LACK OF KNOWN SIALIC METEORITES AND THE PROBABILITY THAT COMPLETE VAPORIZATION WOULD OCCUR FROM THE ENERGY OF IMPACT.

ALTHOUGH THE FIRST OBJECTION RAISES A REAL PROBLEM, TWO WAYS AROUND IT EXIST. THE MOON HAS MORE THAN THE REQUIRED RADIUS TO PRODUCE THE LARGEST CONTINENTS AND HAS VERY NEARLY THE RIGHT DENSITY. WHY THE MOON'S DENSITY IS SO LOW WE DO NOT KNOW AND INDEED UREY (1962) HAS STRUGGLED WITH THIS DIFFICULTY FOR A LONG TIME. BUT IF WE ACCEPT THE MOON AS FORMING SEPARATELY FROM THE EARTH THEN WE HAVE DEMONSTRABLE EVIDENCE THAT CONTINENT-FORMING OBJECTS DID EXIST.

FURTHER, ONE SHOULD NOT EQUATE THE COMPOSITION OF THE PRESENT CRUST WITH THAT OF THE IMPACTING OBJECTS. THE LATTER WOULD HAVE BEEN MODIFIED BY MIXING WITH SURFACE MATERIAL DURING THE COLLISION AS WELL AS BY SUBSEQUENT GEOLOGIC PROCESSES PARTICULARLY INVOLVING INVASIONS FROM THE MANTLE.

THE SECOND OBJECTION OFFERED BY HOWELL TO THE IMPACT THEORY DOES NOT SEEM VERY STRONG, ESPECIALLY IF THE IMPACT WAS NOT HIGHER THAN THE ESCAPE VELOCITY. IF COMPLETE FUSION OCCURS, THE PROCESS WOULD BE AIDED BY GREATER EASE OF BOTH MIXTURE WITH THE MANTLE AND DIFFERENTIATION OF PETROLOGIC COMPONENTS. AT THE PRESENT TIME IT CANNOT BE SAID WITH GREAT

CERTAINTY WHAT PROPORTION OF THE ENERGY OF IMPACT WILL BE INVOLVED IN THE PROCESSES OF MELTING, VAPORIZATION AND SHATTERING.

SOME FRACTION OF THE MATERIAL MUST HAVE SPREAD OVER THE SURROUNDING REGION TO A CONSIDERABLE DISTANCE. GEOLOGIC ACTIVITY OVER 4 BILLION YEARS WOULD HAVE ERASED ANY INITIAL STRUCTURAL DETAILS. THE QUESTION TO BE ANSWERED IS WHETHER SUFFICIENT MATERIAL WOULD REMAIN TO SERVE AS PRIMEVAL CONTINENTS. IN VIEW OF THE DIFFICULTIES WITH GRADUAL FORMATION OF THE CONTINENTS RAISED BY THIS STUDY AND THE FACT THAT CONTINENTS DO EXIST, AN AFFIRMATIVE ANSWER APPEARS TO BE A REASONABLE WORKING HYPOTHESIS.

IF FORMED IN THIS MANNER, GEOLOGICAL PROCESSES WITHIN THE CRUST AND UPPER MANTLE WOULD CERTAINLY HAVE MODIFIED THE ORIGINAL SHAPES, DIMENSIONS AND COMPOSITION OF THE CONTINENTS. IF CONVECTIONAL PROCESSES HAVE OPERATED IN THE MANTLE AS POSTULATED BY SO MANY, THEN CONTINENTAL DEFORMATION WOULD HAVE BEEN RESTRICTED TO THE OUTER RATHER THAN THE INNER PORTIONS OF CONTINENTS. THE RECYCLING OF SEDIMENTS IN THE BORDER REGION WHILE ROCK FROM THE INTERIOR WAS CARRIED OUTWARD ALMOST CONTINUOUSLY MIGHT GIVE THE IMPRESSION OF CONTINENTAL GROWTH BY ACCRETION AT THE MARGINS. AT FIRST GLANCE THIS ACCRETION PICTURE LOOKS MUCH BETTER FOR NORTH AMERICA WITH ITS CENTRAL SHIELD THAN IT DOES FOR THE OTHER CONTINENTS. AND EVEN IN NORTH AMERICA, THE OLDEST ROCK SO FAR RECOGNIZED OCCURS IN THE NORTHERN ROCKY MOUNTAINS WHICH SHOW RECYCLING

AND NEW OROGENIC ACTIVITY AS RECENTLY AS LATE CRETACEOUS, WHILE IN AFRICA AND EURASIA, THE OLDEST ROCKS OCCUR NEAR CONTINENTAL MARGINS.

THE IMPACT HYPOTHESIS DOES NOT PROVIDE IMMEDIATE EXPLANATIONS FOR THE APPARENT DIFFERENCES IN THE NATURE OF THE CONTINENTAL AND OCEANIC MANTLE TO A DEPTH OF SEVERAL HUNDRED KILOMETERS. THE MOST COGENT DIFFERENCES ARE THOSE RELATED TO DIFFERENCES IN SEISMIC VELOCITIES. MACDONALD (1963) SUMMARIZES THE SEISMIC RESULTS AND OFFERS OTHER EVIDENCES FOR DIFFERENCES BETWEEN CONTINENTAL AND OCEANIC MANTLE BASED ON CONCLUSIONS FROM GRAVITY AND THERMAL OBSERVATIONS. ALTHOUGH WE CANNOT AT PRESENT EVALUATE THE EFFECTS OF IMPACT ON THE MANTLE TO A DEPTH OF SOME HUNDREDS OF KILOMETERS, IT MAY BE EXPECTED THAT SOME DIFFERENCES WOULD DEVELOP DURING SEVERAL BILLIONS OF YEARS.

THE SMALL DIFFERENCES IN HEAT FLOW BETWEEN THE CONTINENTAL AND OCEANIC CRUST, THE DATA FOR WHICH ARE ALSO SUMMARIZED BY MACDONALD, CANNOT BE READILY EXPLAINED BY THE IMPACT HYPOTHESIS EXCEPT TO NOTE THAT ORIGINAL DIFFERENCES MAY HAVE BEEN MINIMIZED BY GEOLOGICAL PROCESSES INVOLVING INTERACTIONS BETWEEN THE CRUST AND MANTLE.

UNLESS THE AGE OF THE EARTH IS SUBSTANTIALLY HIGHER THAN 4.5 B.Y. A TERRESTRIAL MECHANISM OF ORIGIN SEEMS UNLIKELY IN VIEW OF THE PRESENCE OF CONTINENTS AND NORMAL GEOLOGICAL PROCESSES AS REMOTE AS 4 BILLION YEARS AGO. WITHOUT A SUBSTANTIAL REVISION OF THE AGE OF THE EARTH WE SUBMIT THAT THE

IMPACT HYPOTHESIS OF ORIGIN IS AS COGENT AS ANY OTHER SO FAR OFFERED. THE ONLY ALTERNATIVE SEEMS TO BE AN ACCUMULATION TEMPERATURE CLOSER TO THE SILICATE MELTING POINT WHICH IS CONTRARY TO THE EVIDENCE FOR COLD ACCUMULATION DISCUSSED PREVIOUSLY.

## CONCLUSIONS

A NUMBER OF GEOLOGICAL AND ASTROPHYSICAL CONCLUSIONS CAN BE DRAWN FROM THE NATURE AND AGES OF THE OLDEST ROCKS, ESPECIALLY WHEN CONSIDERED IN THE LIGHT OF CONCLUSIONS REGARDING THE AGE AND ACCUMULATION OF THE EARTH AND THE EVOLUTION OF THE SUN. WE WISH TO EMPHASIZE THAT MANY OF THESE CONCLUSIONS MUST BE CONSIDERED TENTATIVE PENDING FURTHER INVESTIGATION, BUT WE BELIEVE THE CONCLUSIONS TO BE OF VALUE IN SETTING UP GUIDE LINES AND CERTAIN LIMITING CONDITIONS.

1. INFERENCES FROM RADIOISOTOPE DATES INDICATE THAT AT LEAST PARTS OF THREE MAJOR CONTINENTS WERE PRESENT AT LEAST 4 BILLION YEARS AGO.

2. SINCE THE FINDING OF THE OLDEST ROCK RECORD IS IN PART FORTUITOUS AND IN PART THE RESULT OF SUBSEQUENT GEOLOGIC HISTORY, THE PRIMITIVE CONTINENTS MUST HAVE BEEN CONSIDERABLY LARGER THAN THE REGIONS OF OLDEST ROCK OCCURRENCE.

3. QUARTZ-BEARING SIALIC ROCKS MUST HAVE EXISTED IN THE EARLY CONTINENTS IN AT LEAST SUFFICIENT QUANTITIES NECESSARY TO PROVIDE THE OBSERVED EROSIONAL SEDIMENTS.

4. SUBAERIAL EROSION BY RUNNING WATER MUST HAVE EXISTED AT LEAST 4 BILLION YEARS AGO.

5. ADEQUATE CONTINENTAL RELIEF MUST HAVE EXISTED AT THIS TIME TO INITIATE AND MAINTAIN THE EROSIONAL PROCESS AND TO PROVIDE FOR THE TRANSPORTATION OF THE COARSE SEDIMENTS OF GREAT ANTIQUITY.

6. THE SURFACE TEMPERATURE MUST HAVE BEEN ABOVE FREEZING OVER MUCH OF THE CONTINENTS ABOUT 4 BILLION YEARS AGO.

7. THE PRIMITIVE ATMOSPHERE AT THIS TIME PROBABLY HAD A COMPOSITION SUCH THAT SOLAR LUMINOSITY WAS THE MAJOR FACTOR IN DETERMINING TERRESTRIAL SURFACE TEMPERATURES.

8. ACCORDING TO CURRENT MODELS OF SOLAR EVOLUTION THE SURFACE TEMPERATURES WERE PROBABLY SUBFREEZING. TO ACCOUNT FOR THE AQUEOUS EROSION PROBABLY PRESENT 4 BILLION YEARS AGO IT MAY BE IN ORDER EITHER TO PUSH BACK THE AGES OF THE EARTH AND SUN OR TO MODIFY THE MODELS USED TO SOME EXTENT.

9. RATES OF EROSION ARE PROPORTIONAL TO TEMPERATURE, HUMIDITY AND VEGETATION. AS THESE PROBABLY ALL INCREASED DURING GEOLOGIC TIME, IT SEEMS THAT SEDIMENTATION RATES SHOULD ALSO HAVE INCREASED WITH CONSEQUENT DECREASE IN THE LENGTH OF GEOSYNCLINAL CYCLES.

10. FROM PUBLISHED CALCULATIONS ON THE THERMAL HISTORY OF THE EARTH IT CAN BE CONCLUDED THAT THE MELTING OF SILICATES IN THE MANTLE WOULD NOT HAVE OCCURRED DURING THE FIRST BILLION YEARS OF EARTH HISTORY. THIS SEEMS TO OBTVIATE THE POSSIBILITY THAT CONTINENTS FORMED BY ANY SEGREGATION PROCESS FROM THE MANTLE UNLESS THE EARTH WERE CONSIDERABLY OLDER THAN 4.5



BILLION YEARS.

11. THE ALTERNATIVE PROPOSAL IS OFFERED THAT THE CONTINENTS ORIGINATED FROM THE IMPACT OF A SWARM OR SWARMS OF LOW DENSITY METEORITIC MATERIAL NOT NECESSARILY OCCURRING SIMULTANEOUSLY. FUSION AND ADMIXTURE WITH MANTLE MATERIAL BY GEOLOGIC PROCESSES WOULD HAVE MODIFIED THE ORIGINAL MATERIAL INTO THE PRESENT CONTINENTS, WHICH FOR THE MOST PART SEEM TO CONSIST OF RECYCLED SEDIMENTARY ROCKS. THE UNSTABLE CONTINENTAL MARGINS WOULD TEND TO SUFFER FAIRLY CONTINUAL OROGENY CREATING THE PERHAPS MISLEADING IMPRESSION OF ACCRETION AROUND A CENTRAL NUCLEUS OR CRATON.

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### LEGEND FOR ILLUSTRATIONS

FIG. 1. THE VARIATION OF SOLAR LUMINOSITY WITH TIME IN TERMS OF THE RATIO OF THE PAST LUMINOSITY ( $L$ ) TO THE PRESENT LUMINOSITY ( $L_0$ ) (BASED ON THE CALCULATIONS OF HASELGROVE AND HOYLE, 1959)

FIG. 2. TEMPERATURE VARIATION IN A HOMOGENEOUS EARTH OF CHONDRITIC COMPOSITION HAVING AN INITIAL TEMPERATURE OF  $1300^{\circ}\text{C}$ . (AFTER MACDONALD, 1959)